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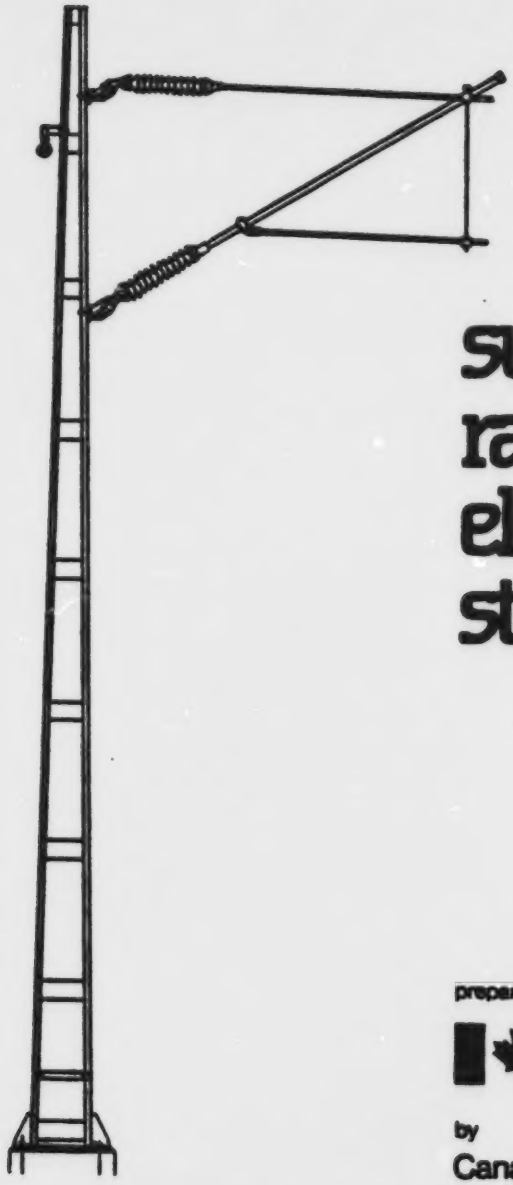

suggested railway electrification standards

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SUGGESTED RAILWAY ELECTRIFICATION STANDARDS

by

G.B. Furst

and

L.C. Tait

CANADIAN PACIFIC CONSULTING SERVICES LTD.

March 1984

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17. Abstract

This document proposes draft electrification standards for Canadian railway electrification in the 25 kV to 50 kV 60 Hz range. It addresses the mechanical and electrical design of overhead contact systems, insulation and electrical clearances, electromagnetic interference to communications and signals, interface with electric utilities as well as grounding and safety requirements.

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17. Résume

Ce document suggère des normes d'électrification pour l'électrification ferroviaire canadienne dans la gamme de 25 kV à 50 kV 60 Hz. Il examine la conception mécanique et électrique de systèmes de contact aérien, l'isolation et l'isolement électrique, l'interférence électromagnétique aux systèmes de communications et de signalisation, l'interface avec les utilités électriques publiques ainsi que les besoins en systèmes de sécurité et mise à terre.

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25 kV to 50 kV RAILWAY ELECTRIFICATION

1. SCOPE

1.1 This Standard applies to mainline and intercity railway and rapid transit systems using single phase alternating current (ac) supply to the locomotive in the range of 25 kV to 50 kV.

1.2 This Standard covers design criteria and design requirements in the following selected areas of railway electrification. It is not a complete draft of a railway electrification standard.

1.2.1 Insulation Coordination and Electrical Clearances.

1.2.2 Vertical and Horizontal Clearances.

1.2.3 Overhead Contact Systems (OCS).

1.2.4 Interference with Signalling and Communications Circuits.

1.2.5 Utility Interface - Unbalance and Harmonics.

1.3 The requirements contained in this Standard do not constitute complete design or construction specifications but only prescribe minimum design requirement.

1.4 Conditions not covered herein shall be governed by the appropriate requirements or equivalent standards in common use or as required by constituted authority.

1.5 In addition to the related standards listed under the Reference Publications, the standards and guidelines of the American Railway Engineering Association and U.I.C. (Union International des Chemins de Fer) may be used in areas not covered by this Standard.

2. DEFINITIONS

2.1 The following terms are frequently used in railway electrification work.

Bond

an electrical connection between metal hardware to eliminate static discharge

bond, rail - electrical connection between adjacent lengths of rail

bond, impedance - a magnetic device connected across rails allowing the traction return current to by-pass insulated rail joints.

Carbon Collector (Pantograph shoe)

the carbon strip on top of the pantograph which slides along the contact wire

Contact Wire

the wire with which the pantograph or current collector is designed to make contact, also called trolley wire

Weight Tensioning Assembly

the weighted tensioning device at each end of the tension section, sometimes called counterbalance, or regulating equipment

Cantilever

the support frame and registration assembly supporting the catenary from a pole, sometimes called a crossarm

Deadend

a tensioned conductor termination without counterweight

Electrical Clearance

passing - air clearance between live parts of either the vehicle or catenary and grounded parts of the fixed structures. It exists during the passage of the locomotive or car

static - air clearance between live parts of a catenary structure and grounded parts of a fixed structure, under non-passing conditions

Gradient, Contact Wire

the average slope of the contact wire relative to the track between two supports

Grounded

connected to the common return of the system and/or the conducting mass of the earth

Grounding Wires

the conductor(s) installed for the purpose of providing electrical continuity usually between the supporting structures of the overhead equipment and the common return of the system (rails, return wire, impedance bonds)

Dropper

a fitting by means of which the contact wire is suspended from the messenger wire, sometimes called a hanger

Headspan

a multi-track catenary support structure consisting of two vertical columns supporting wires spanning the tracks, with the catenary support and registration equipment attached to the spanning wires

Horns

the bent or angled-downwards portion of the pantograph at either end of the carbon collector

Jumper

generally an internal electrical connection in the overhead contact system, a short conductor installed to provide electrical continuity

overlap - a full-current jumper at tensioning overlaps

feeder - an electrical connection from feeder to overhead contact system

potential equalizer - a light internal jumper across the dropper and between the messenger and contact wires

full-current - a jumper of equivalent current capacity as the overhead contact system

Load Gauge

the maximum height of a load or rail car allowed on a track

Messenger

the wire from which the contact wire is suspended by means of droppers

Offset

deviation of the static contact wire from the superelevated centerline of the track

Overhead Contact System (OCS)

that part of the overhead equipment comprising the catenary, supports, foundations, counterweights and other equipment and assemblies, that delivers electric power from the traction sub-station to the locomotives

Overlap Arrangement

that portion of the overhead contact system where two adjoining tension sections overlap and terminate

Pantograph

the current collector on top of a locomotive

Phase Break

an insulated separation between two electrical sections of the overhead contact system fed from different phases under which a pantograph may pass without shorting the phases

Portal

a frame support structure consisting of vertical columns supporting each end of an horizontal beam which crosses one or more tracks to support the catenary

Pull Off/Push Off

the registration towards or away from the centerline of the track in relation to the pole

Return Wire

a conductor, normally mounted directly on the pole, that provides a low-impedance current return to the substation

Registration

lateral support of catenary conductors

Section

electrical section - the electrical circuit beyond one or between two or more switching points

tension section (for constant tension catenary) - part of the overhead contact system between two tensioning devices where the conductors are kept under constant tension

Section Break

an electrical break in the overhead contact system permitting isolation of a section of catenary

Stagger

the offset of the contact wire at a support due to registration

Steady Arm

the rod and contact wire clamp assembly that permits lateral restraint of the contact wire without obstructing the passage of the pantograph

Uplift

dynamic - lift of the conductor due to the pantograph passing

static - lift of the conductor due to the stationary pantograph

3. INSULATION CO-ORDINATION AND ELECTRICAL CLEARANCES

3.1 GENERAL

The insulation and/or clearances between wires forming the OCS and ground and between OCS wires which can be live or grounded has to be such that the probability of damage to equipment and loss of power supply is reduced to a technically and economically acceptable level.

This implies the careful selection of insulation levels, clearances and insulation protective devices to ensure both the integrity of the insulation of one element and that of the whole system. Lack of co-ordination resulting in overinsulation of a group of components can increase the exposure of other components.

3.2 VOLTAGE CLASSIFICATION

Nominal voltage is the r.m.s. value of the single phase ac voltage between the OCS conductors and rails or OCS conductors and ground by which the OCS is designated and to which certain operating and equipment characteristics, insulation levels and clearances are related. It can be, but it is not necessarily the normal voltage maintained at any point in the system.

25 kV and 50 kV are the only two nominal voltages covered by this Standard.

Highest system voltage is the maximum value of the OCS power frequency r.m.s. operating voltage which can be sustained on the OCS and power supply system. The OCS voltage distorted by harmonics may have peaks in excess of the undistorted power frequency voltage by no more than five percent.

Highest system voltages are given in Table 3.1. Clearances and insulation levels are based on the highest system voltage.

3.3 OVERVOLTAGES

Overvoltages are classified according to their duration, frequency and origin. The four principal categories are:

3.3.1 Temporary or power frequency overvoltages usually caused by sudden change in traction load, switching of shunt capacitor filters or sections of the OCS. The duration of such overvoltages usually does not exceed a few seconds.

3.3.2 Harmonic and resonant voltages caused by the interaction of narmonic injection into the OCS by thyristor converters on locomotives and the harmonic impedance of the OCS and power supply system. Such overvoltages are a function of the locomotive converter firing angle and load. They can be sustained for the duration of the critical loading conditions and firing angles.

3.3.3 Switching impulse overvoltages are usually caused by closing or opening of circuit breakers in the OCS and power supply system. Their frequency is in the range of a few hundred to a few thousand Hz and their duration is a few ms.

3.3.4 Lightning impulse overvoltages are caused by lightning striking the OCS. The typical lightning surge has a duration of up to a few hundred microseconds and a steep front of one to five microseconds.

Table 3.1 gives some typical overvoltage ratios for the four classes of overvoltages. The overvoltage ratio $U_{OV\ peak}/U_{H\ peak}$ is the ratio of the peak value of the overvoltage to the peak value of highest system voltage.

TABLE 3.1

TYPICAL OCS OVERVOLTAGE RANGES

Voltage Class	Highest System Voltage	Overvoltage Factor $U_{OV\ peak}/U_{H\ peak}$			
				Switching	Lightning
kV	kV rms	Temporary	Harmonic	Impulse	Impulse
25	27.5	1.05-1.15	1.05-1.10	1.8-2.2	10-20
50	55	1.05-1.25	1.05-1.10	1.8-2.2	5-10

3.4 CRITERIA FOR ELECTRICAL CLEARANCES AND INSULATION LEVELS

3.4.1 Electrical

Clearances and insulation levels should be selected in such a manner that the risk of flashovers and insulation breakdown is kept below one percent for temporary, harmonic and switching impulse overvoltages.

3.4.2 To design overhead contact systems for a given trip out rate per 100 km per year for lightning impulse overvoltages is prohibitively expensive and is not justified under the low isokeraumic levels encountered in Canada.

3.4.3 Where the system voltages and overvoltage factors fall within the range of values given in Table 3.1, clearances and insulation levels given in Clauses 3.5 and 3.6 shall be used.

3.4.4 The insulation of substation and other power supply equipment such as transformers, voltage and current transformers, circuit breakers and harmonic filters shall be protected by surge arresters against lightning impulse overvoltages.

3.4.5 Where the system voltages and overvoltage factors exceed the highest values given in Table 3.1, or abnormal conditions not given in

Clauses 3.5 and 3.6 exist, clearances and insulation levels shall be determined in accordance with the principles outlined in the Canadian Standard CAN-C308-M80 "The Principles and Practice of Insulation Co-Ordination".

TABLE 3.2
ELECTRICAL CLEARANCES

Voltage Class kV	Highest System Voltage kV rms	Static Clearance mm	Passing Clearance mm	Minimum Clearances mm	
				Static	Passing
25	27.5	250	200	200	150
50	55.0	500	400	400	300

3.5 ELECTRICAL CLEARANCES

3.5.1 Definitions

For the purpose of insulation coordination and determining the electrical parameters of clearances, they should be classified as follows:

3.5.2 Static Clearances

3.5.2.1 Static clearance is deemed to be the minimum design clearance to be maintained within the range of the design ambient temperatures and overhead contact system operating temperatures, 90% probability wind pressure and no pantograph pressure on the contact wire except under conditions listed in Clause 3.5.2.2.

Static clearance shall be maintained between:

a) Normally live conductors or parts of the OCS where one conductor can be de-energized or energized from a different source.

b) Normally live conductors or parts of the OCS and structures, walls or grounded parts of the OCS.

c) Normally live conductors or parts of the OCS and the fictitious loading gauge line.

d) Any part of the raised pantograph and the conductors belonging to the OCS conductors associated with a parallel track.

e) Any part of the raised pantograph and structures and grounded components of the OCS.

f) Any part of the raised pantograph and any normally live or grounded part on the roof of the locomotive.

3.5.2.2 Notwithstanding Clause 3.5.2.1, in stations, railyards and sidings all clearances shall be maintained with full design pantograph pressure and with due regard to the oscillation of the OCS conductors resulting from the pantograph pressure.

3.5.3 Passing Clearances

3.5.3.1 Passing clearance is deemed to be the reduced clearance which can be sustained temporarily under the following conditions:

a) Maximum design pantograph pressure on the contact wire.

b) Wind in excess of 90% probability wind velocity.

c) Clearance reduction caused by rolling or pitching motion of rolling stock.

d) Track Standard Tolerances.

e) Under conditions given in Clause 3.5.3.2.

3.5.3.2 Passing clearance is permissible between parts of the pantograph and any adjacent structure, wall, part of the OCS and energized or grounded part of the OCS of a parallel track in tunnels, bridges, on over and underpasses under the following conditions:

a) The length of tunnel, bridge, overpass or underpass does not exceed 100 m.

b) There is no scheduled or envisaged stopping of trains within the section where the passing clearance applies for reasons other than emergency.

3.5.3.3 Notwithstanding Clauses 3.5.3.1 and 3.5.3.2 clearances cannot be reduced below the value of the static clearance in stations, railyards and sidings.

3.5.4 Minimum Clearances

3.5.4.1 The minimum value of static and passing clearances shall be those given in Table 3.2.

Minimum clearances are applicable to standard atmospheric conditions, to an altitude of 1000 m above sea level and clean air. Clause 3.5.4.2 gives the calculation of correction factors for non-standard ambient conditions.

3.5.4.2 Standard atmospheric condition for the application of minimum clearances is deemed to be a relative air density of 1.0 and a humidity of 11 mg/m^3.

The relative air density (RAD) can be calculated from the following relation:

$$RAD = \frac{2.89b}{273+t}$$

where

b = barometric pressure in kilo Pascals (kPa)

t = temperature in degrees Celsius

Minimum clearances do not have to be corrected for the departure from standard humidity.

For a RAD less than 93 percent corresponding to the average air density at 1000 m altitude, the minimum clearances shall be increased by one percent for each one percent reduction in the RAD.

The minimum clearances shall be increased by one percent for each two degrees by which the maximum temperature exceeds +40 degrees Celsius.

3.5.5 Special Clearances

Special clearances, different from those given in Table 3.2 shall be used under the following conditions.

3.5.5.1 Altitude above 1000 m

For any track section longer than 100 m and at an altitude exceeding 1000 m above sea level, all electrical clearances shall be increased by an amount given in Clause 3.5.4.2.

3.5.5.2 Atmospheric Pollution

Non-polluted atmosphere shall be deemed to be an OCS environment where an OCS insulator over a period of one month will not assume a surface contamination greater than to 0.2 mg/cm^2 NaCl or where there is no substantial accumulation of diesel or other combustion engine exhaust fumes. (e.g. long tunnels with mixed diesel and electric traction). For a polluted atmosphere there may be a need to increase the leakage distance of insulators as outlined in Clause 3.6. For air clearances, however, the values given in Table 3.2 contain sufficient margin to cater to these conditions.

3.5.5.3 Reduction in Maximum Temperature

If there is a substantial reduction in the maximum ambient temperature from 40 degrees Celsius assumed for the clearances given in Table 3.2, as could be the case in long tunnels, the clearances shown in Table 3.2 may be reduced by 3% for every 10 degrees Celsius reduction in maximum ambient temperature below 40 degrees Celsius.

3.5.5.4 Restricted Openings

Special reduced clearances may be used on bridges, in tunnels, underpasses and other structures. Such reduced clearances shall be based on an in-depth insulation co-ordination study and preferably laboratory tests.

3.5.5.5 Polluted Atmosphere and Hazardous Conditions

For polluted atmosphere and hazardous conditions such as explosive atmosphere, increased clearances may be required which shall be determined based on studies or laboratory tests.

3.6 ELECTRICAL CHARACTERISTICS OF OCS INSULATORS

3.6.1 Application

The scope of this Clause includes all insulators associated with the OCS and switchgear insulators in traction substations and OCS sectionalizing equipment. Phase break and OCS section insulators used in line with the contact and messenger wire are excluded.

3.6.2 Atmospheric Conditions

Electrical characteristic given in Table 3.3 apply to standard atmospheric conditions as specified in Clause 3.5.4.2 and a non-polluted atmosphere as specified in Clause 3.5.5.2.

3.6.3 Insulator Electrical Characteristics

The 60 Hz power frequency withstand voltage, the lightning impulse withstand voltage (BIL) and the minimum surface leakage distance of OCS insulators are given in Table 3.3.

3.6.4 Correction Factors for Atmospheric Conditions

3.6.4.1 The values in Table 3.3 shall be used up to an altitude of 1000 m above sea level. For higher altitudes all values given in Table 3.3 shall be increased by one percent for each 100 m increase in altitude above 1000 m.

3.6.4.2 The values in Table 3.3 shall apply within the temperature range of 40 degrees Celsius maximum and -45 degrees Celsius minimum ambient temperature without correction.

3.6.4.3 For polluted atmospheric or hazardous atmospheric conditions special insulators shall be used as recommended by insulator manufacturers or high voltage laboratories specializing in this field.

TABLE 3.3
ELECTRICAL CHARACTERISTICS OF OCS INSULATORS
AND HIGH VOLTAGE

Voltage Class kV	Highest System Voltage kV rms	Power Frequency[1] Withstand kV rms	Lightning Impulse Withstand - BIL kVp	Insulator Surface Leakage Distance mm
25	27.5	60	150	725
50	55.0	120	300	1,450

Note 1: Wet for outdoor, dry for indoor insulators

3.7 ELECTRICAL INSULATION CHARACTERISTICS OF HIGH VOLTAGE SWITCHGEAR AND TRANSFORMERS

3.7.1 Application

This Clause applies to all 25 kV or 50 kV switchgear and transformers forming part of traction power feed substations or equipment and transformers connected to the OCS such as trackside power supplies, harmonic filters, series capacitors, etc.

3.7.2 Insulation characteristics of switchgear and transformers shall be as given in Table 3.3.

3.7.3 Correction factors for atmospheric conditions shall apply to external insulation only as specified in Clause 3.6.4. No correction factor shall be used for insulation under oil or gas.

3.8 OCS PHASE BREAKS AND SECTION INSULATORS

3.8.1 Phase Break Insulator Assembly

The minimum clearance between any part of the normally energized section of the assembly and the normally dead and/or grounded center section shall be at least the Static Clearance. The minimum clearance between any two points of the normally energized right hand and left hand sections shall be at least twice the Static Clearance.

3.8.2 Section Insulator Assembly

The minimum clearance between any two points between the right and left hand side of the insulator assembly shall be at least 1.25 times the Static Clearance.

3.9 PARALLEL TRACK CIRCUITS

3.9.1 The horizontal clearance between the nearest normally energized parts of adjacent track overhead circuits shall not be less than twice the static clearance except in crossings or overlaps where the following clearances shall be maintained.

If the two track circuits can only be energized from the same phases of the same power source, the minimum clearance between two normally energized points of the two track circuits shall not be less than the static electrical clearance. If the two track circuits can be energized from different phases or different power sources the minimum clearance shall be at least twice the static electrical clearance.

3.9.2 If maintenance work has to be performed on a track circuit with an adjacent track circuit energized the layout of the OCS has to be such that a workman, or any tool he has to use, will not approach live conductors nearer than 2.75 m.

3.9.3 The distance specified in Clause 3.9.2 may be reduced if special measures are taken for repair and maintenance work such as erection of a temporary screens.

4. VERTICAL AND HORIZONTAL CLEARANCES

4.1 GENERAL

Vertical and horizontal clearances are construction clearances which include the following:

a) The load gauge.

b) The uplift of the OCS caused by pantograph pressure.

c) Civil engineering tolerance in construction and maintenance of the track and the OCS.

d) Depth of the OCS between contact wire and messenger wire.

e) The electrical clearance between the energized overhead contact system and surrounding structures.

f) The electrical clearance between the contact wire and the static and kinematic load gauge.

4.2 COMPONENTS OF CONSTRUCTION CLEARANCES

4.2.1 Load Gauge

The height of the normal load gauge may vary in the range of 6.0 to 7.5 m.

Abnormal load heights may be accommodated by the use of dead wire catenary sections or by de-energizing sections of the catenary.

4.2.1.1 Static Load Gauge

The static load gauge is assumed to be the envelope of load gauges taking the super-elevation of the rails into account in curves. When determining the static load gauge the maximum value of super-elevation is assumed to be above the other rail at zero elevation. The maximum vertical height of the static load gauge Y_S is the difference in elevation between the highest point of the static load envelope and the non-elevated rail.

4.2.1.2 Kinematic Load Gauge

The kinematic load gauge is the envelope of load gauges taking into account the dynamic motion of rolling stock superimposed on the regular movement along the tracks. The kinematic load gauge includes the effect of super-elevation of rails. The maximum vertical height of the kinematic gauge Y_K is the difference in elevation between the highest point of the envelope and the non-elevated rail.

4.2.2 Depth of OCS Construction

The depth of the overhead contact system D_C is the difference in vertical height between the contact wire and the messenger wire, normally measured at the point of support.

4.2.3 OCS Uplift

The OCS uplift is the maximum dynamic vertical displacement L_1 of the messenger wire, or contact wire in the absence of messenger wire, due to pantograph pressure on the contact wire, wire oscillations induced by pantograph pressure and wind (Gallopping). The OCS uplift is the maximum displacement from the position of the wire at rest and not the amplitude of oscillations.

4.2.4 Construction Tolerances

An allowance B equal to at least 25 mm shall be made for future raising of track or ballasting.

An erection tolerance T equal to at least 50 mm shall be made to allow for erection inaccuracies and misalignments in the OCS system.

4.2.5 Electrical Clearances

Static electrical clearances C and passing electrical clearances P are defined in Clause 3.5.

4.3 VERTICAL CLEARANCE AND STRUCTURE OPENING

4.3.1 Vertical Clearance

The minimum vertical clearance between contact wire and the top of the non-superelevated rail shall be determined from the formula:

$$H_V = Y_S + C + T + B$$

where

Y_S = the height of the static load gauge

C = static electrical clearance

T = OCS erection tolerance

B = allowance for raising the tracks

as shown in Figure 4.3

4.3.2 Vertical Structure Opening

The minimum vertical structure opening shall be determined from the following formula:

$$H_{VS1} = B + Y_S + C + D + T + C$$

$$= B + Y_S + 2C + D + T$$

or

$$H_{VS2} = B + Y_K + L + P + D + T$$

whichever yields the greater vertical opening.

In the above formula:

H_{VS1} = vertical opening if the static electrical clearance governs

H_{VS2} = vertical opening if the dynamic conditions govern

B = allowance for track raising

Y_S = static load gauge

Y_K = kinematic load gauge

C = static electrical clearance

P = passing electrical clearance

L = construction tolerance

D = depth of OCS construction

4.4 HORIZONTAL STRUCTURE OPENING

The minimum horizontal structure opening is a complex function of the track and OCS layout in tunnels, underpasses, on bridges and in other structures. The horizontal opening should be determined by judicious application of the rules in Clauses 3 and 4.1 to 4.3.

As a general guide and applicable only to the opening at the level of the pantograph the minimum horizontal opening can be determined from:

$$H_{hp} = 2S + 2P + X + 2T_h + 2E$$

where

H_{hp} = minimum structure opening at pantograph level

P = passing electrical clearance

X = width of the pantograph

S = horizontal pantograph sway including effect of superelevation

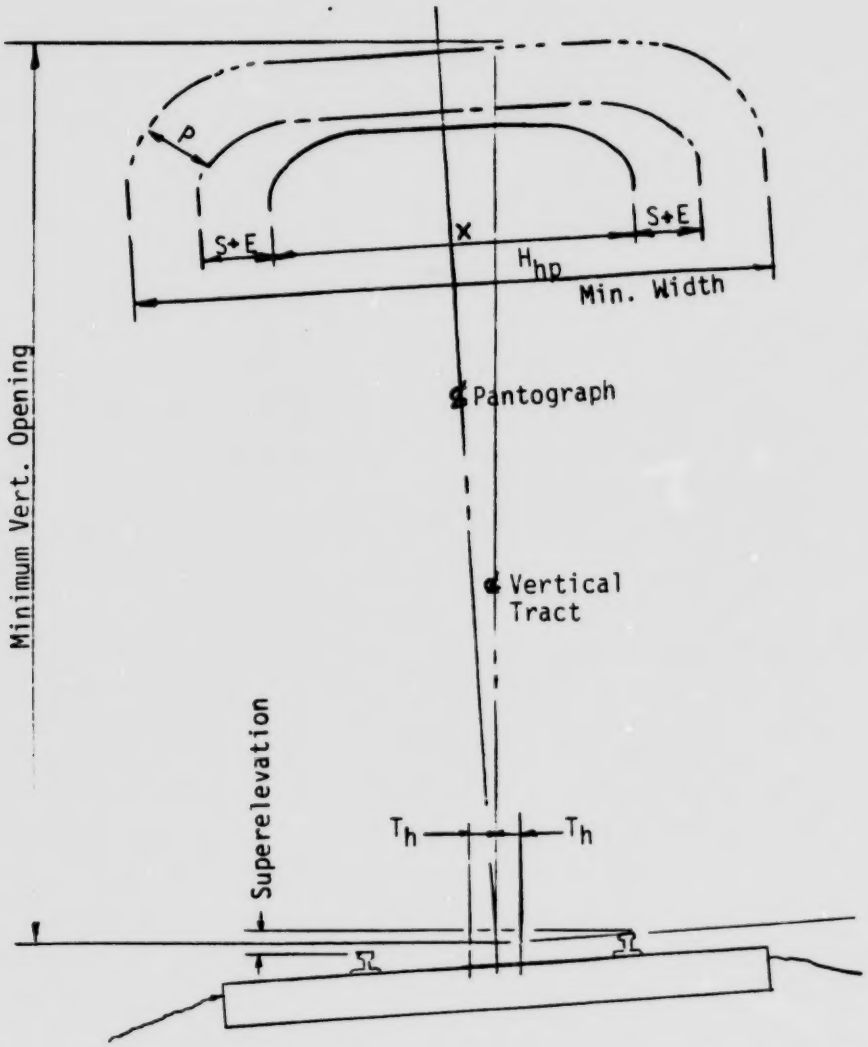
T_h = lateral construction tolerance of tracks

E = allowance for locomotive displacement due to its suspension

as shown in Figure 4.3

4.5 OCS MAST SETBACK

The OCS mast setback is the horizontal distance between the center line of the track and the mast or vertical member of the portal structure supporting the cantilever. The mast setback is governed by the operating and maintenance rules and considerations prevailing in the railway company. The setback is normally not dependent on electrical clearances. A usual setback of masts is in the order of 3.5 m.



$H_{hp} = 2S + 2P + X + 2T_h + 2E$

where

H_{hp} = minimum structure opening at pantograph level

P = passing electrical clearance

X = width of the pantograph

S = horizontal pantograph sway including effect of superelevation

T_h = lateral construction tolerance of tracks

E = allowance for locomotive displacement due due to its suspension

FIGURE 4.3

5. OVERHEAD CONTACT SYSTEMS (OCS)

5.1 OCS configurations commonly used in high voltage electrification are illustrated in Figure 5.1 and described as follows:

5.1.1 Simple catenary (level contact) (maximum speed 120 km/h) - comprises a messenger wire with hangers spaced uniformly along it, supporting the contact wire, which assumes a level profile in relation to the track.

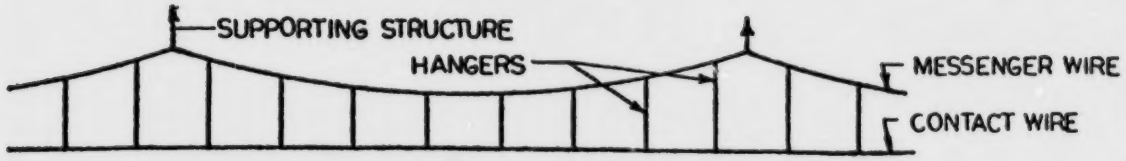
5.1.2 Simple catenary (sagged contact) (maximum speed 175 km/h) - comprises a messenger wire, uniformly spaced hangers and a contact wire but with the introduction of pre-determined sag into the contact wire. This improves the mechanical stiffness under dynamic conditions and permits higher speed operations than does the level contact configuration.

5.1.3 Simple stitched catenary (maximum speed 250 km/h) - similar to the simple catenary but has additional ''stitch'' wires in the vicinity of the supports to reduce the stiffness.

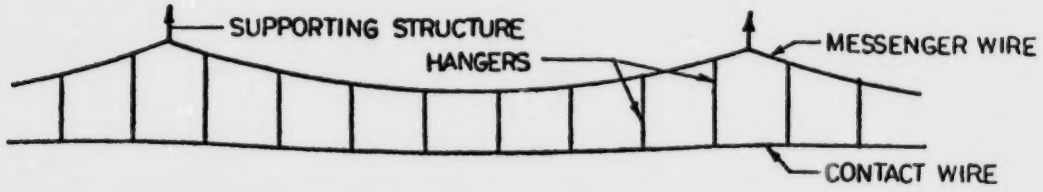
5.1.4 Compound catenary (maximum speed 300 km/h) - comprises a contact and main messenger wire with an auxiliary messenger continuously interposed between them. This provides improved current collection characteristics for very high speeds.

5.1.5 Single wire catenary (trolley wire) (maximum speed 50 km/h) - comprises of either a contact wire alone or a contact wire with auxiliary support wires. The single trolley wire is commonly used for slow speed applications such as yard trackage. Using an additional auxiliary support wire permits longer spans.

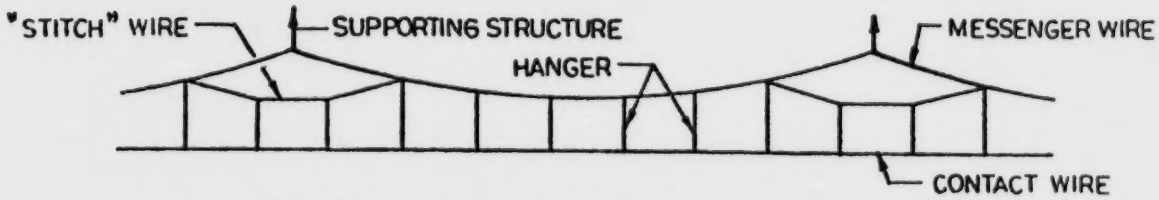
Figure 5.1



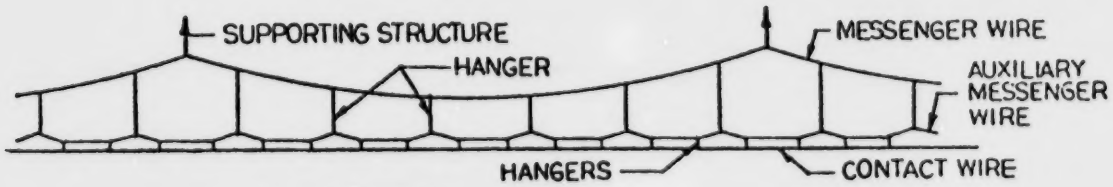
SIMPLE CATENARY (LEVEL CONTACT)



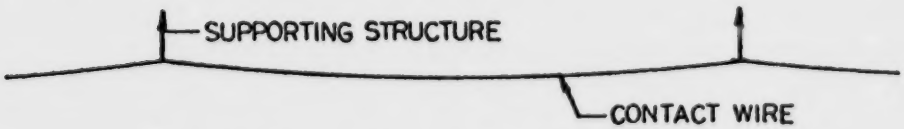
SIMPLE CATENARY-(SAGGED CONTACT)



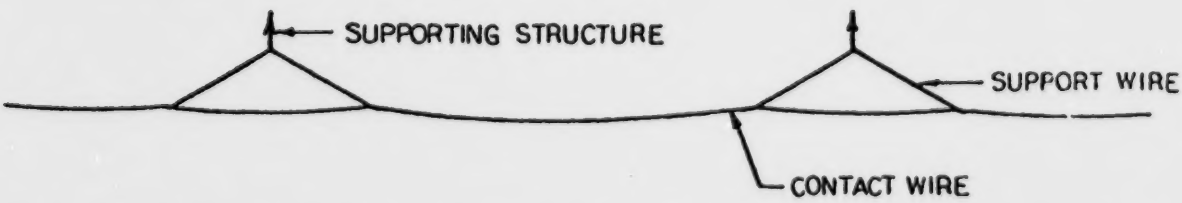
SIMPLE STITCHED CATENARY



COMPOUND CATENARY



SINGLE WIRE CATENARY (TROLLEY WIRE SYSTEM)



SINGLE WIRE CATENARY(TROLLEY WIRE SYSTEM WITH SUPPORT WIRES)

5.2 VARIABLE AND CONSTANT TENSION SYSTEMS

5.2.1 An important parameter in the system design is the tensioning of the various wires. The tension in the wires has a direct effect on the deflection of the wires as a result of wind-loading, and the operating speed of the system as determined by the critical speed.

There are two methods possible for tensioning the system: a constant-tension (regulated) system and a variable-tension (unregulated) system. In a variable-tension system, the wires are initially tensioned and then fixed in place. The tension in the wires is then directly dependent upon temperature contraction and expansion.

Some systems use the same tensions in the messenger as in the contact wire and others use a different tension in the messenger from that in the contact wire.

In constant tension systems using copper contact wire, the tension in the contact wire should not exceed 110 N/mm^2.

The critical speed of a system is directly dependent upon the tension in the wires. If the operating speed is equal to the critical speed, the catenary is set in resonance and the amplitude of the pantograph becomes uncontrolled.

5.2.2 Span lengths shall be determined in consideration of the following factors:

- tension limitations to obtain vertical clearances (i.e. messenger sag is proportional to the square of the span length);
- contact wire displacement limits;
- radial loads on structures resulting from track curvature;
- optimal (economic) support structure sizes for imposed loads.

5.2.3 The maximum span is calculated from the formula:

$$d = \frac{wL^2}{8T}$$

$$\text{and } L = \sqrt{\frac{8\ Td}{w}} \text{ meters}$$

where d = worst permitted blow-off in meters

T = tension in newtons

w = sum of contact and messenger wind pressure in newtons/sq. meter.

5.2.4 The system shall be designed such that the operating speed is either greater than or less than the critical speed. In general, to avoid the rough transition period near the critical speed, the operating speed should be less than the critical speed.

Critical speed $V_c = \sqrt{\frac{\Sigma T}{\Sigma \rho}}$ where T = tension in newtons and ρ = mass per unit length of the OCS in kg sec^2/m.

High tensions result in increased loads on supporting structures, necessitating stronger members.

The OCS shall be designed to provide static and passing clearances when subjected to pantograph pressures.

5.3 PRE-SAG

5.3.1 With an initially horizontal contact wire, a pantograph shoe follows a trajectory which is higher at mid span than at the supporting structure. This results in the creation of a travelling wave in the contact wire of which the reflective wave can interfere with current collection by the pantograph(s).

A simple catenary OCS contact wire shall be pre-sagged by an amount sufficient to counteract the creation of these oscillations. This amount is usually 1/1000 of span length.

5.4 PANTOGRAPHS

5.4.1 The OCS shall be designed for the pantograph(s) to be used on it. The mass of the pantograph, its static and dynamic uplifts and its profile shall be considered.

5.4.2 Pantograph upward force significantly affects current collection, improving it with increasing pressure. Too great a pressure may result in increased wear on the shoe and on the contact wire. Too small a pressure may lead to poor current collection, arcing and electric wear on the shoe and contact wire.

5.4.3 Loss of contact (de-wiring) shall be restricted to less than 2%.

5.4.4 Pantograph static pressure shall be 60-70 N for contact wire tensions of the order of 10 kN.

5.4.5 Pantograph dynamic pressure shall be less than 120 N for contact wire tensions of the order of 10 kN.

5.4.6 Damping between the pantograph shoe and frame will tend to absorb vibrational energy and improve current collection. It shall not, however, be so large as to "freeze" the motion of the shoe with respect to the frame.

Damping between the frame and the car will arrest the downward motion of the pantograph as it passes beneath the cantilever thus effectively making a hard spot of it.

5.4.7 If the train utilizes more than one pantograph, the additional pantographs' deflections may augment that of the first and so on. Pantographs must be so spaced that their deflections occur in opposition to each other as far as possible.

5.5 STAGGER

5.5.1 To equalize wear on the pantograph shoe, the contact wire shall be staggered on opposite sides of the track centre line on tangent track and towards the outside of the curve on curved track.

The amount of stagger is a function of the permissible displacement due to all causes and pantograph width.

It varies from ±100 mm to ±450 mm.

5.6 GRADING

5.6.1 The contact wire grade (slope) shall not exceed 2%.

Recommended maximum gradients are:

A.	Yard conditions	2.3%
B.	50 km/hr	1.3%
C.	75 km/hr	0.8%
D.	100 km/hr	0.6%
E.	125 km/hr	0.5%
F.	150 km/hr	0.4%
G.	200 km/hr	0.3%

5.6.2 Except for yard conditions, the change of grade from one span to the next should not exceed one half of the values shown.

5.7 PHYSICAL CLEARANCE

5.7.1 The contact wire height shall provide load gauge plus electrical clearances (see section 3.4).

5.7.2 Clearances over roads shall conform to the requirements of CSA standard C22.3 No. 1-M1979.

5.7.3 The lateral physical clearance between the pole face and the nearest rail shall be as small as possible while not encroaching upon clearance diagram requirements.

Snowplow and wide load requirements shall be considered.

Poles shall not obstruct signals.

A clearance of 2440 mm on tangent track is desired. It shall be increased on curves to compensate for locomotive and car protrusions.

5.8 WIRE

5.8.1 The number, type and size of wires comprising the overhead contact system is dictated by many factors. They depend first of all upon the OCS configuration (of figure 5.1) selected, current carrying capacity, impedance and permissible voltage drops. Strength, wear and corrosion resistance are other factors. An optimal selection must also consider the economies.

5.8.2 Grooved, hard drawn copper is frequently used for the contact wire. A cross-sectional area of 107 mm^2 has been found to be an economical choice for 25 kV and 50 kV systems and have the required current carrying capacity at 30% wear.

Where higher strength and increased resistance to wear are required, cadmium bronze has been used although this practice is disappearing.

5.8.3 Messenger wire selection depends upon strength, weight, current carrying capacity and its operating environment. Where weight is of concern and the environment is not corrosive, Aluminum Cable Steel Reinforced (ACSR) of equivalent strength and current carrying capacity is suitable.

ACSR has a tendency to creep upon initial stringing and pre-stressing or design allowances must be made. The use of ACSR in conjunction with copper can cause galvanic problems and suitable clamps, connectors, etc. must be used.

5.8.4 Current carrying capacity shall consider the following:

- Maximum permissible temperature for conductor material. (80°C for HD copper);
- Ambient wind speed;
- Intensity of solar radiations;
- Maximum ambient temperature;
- Absorption coefficient;
- Conductor emissivity;
- Electrical heating (I^2R)

5.8.5 Ground Return, Feeder and Protection Wires

ACSR of appropriate size is suitable for ground return, feeder and protection wires in non-corrosive environments.

5.8.6 Jumpers should be fabricated from stranded flexible soft drawn copper of suitable ampacity. Potential equalizing between the messenger and the contact wire across droppers shall be provided as determined by differential voltage drop calculations.

5.8.7 Concentric Lay Stranded flexible copper of suitable ampacity shall be used for ground connections from poles to rail.

5.8.8 Galvanized steel wire strand of appropriate strength is suitable for guying and for mid-point anchors. The specific guying requirements must be calculated in each case.

5.8.9 Stainless steel non-rotating flexible wire rope shall be used for weight tensioning assemblies. Its dimensions and strength are dependent, upon pulley diameters, assembly pulley ratio and safety factor.

5.9 SYSTEM DEPTH (ENCUMBRANCE) AND DROPPERS

5.9.1 System depth is a mechanical measurement resulting from many factors and optimized for particular systems on the basis of experience. It is dictated by the minimum required separation between the messenger and a contact wire at mid-span (150 mm), tensions, span length, structural strength requirements, dropper lengths, clearances, etc.

Since excessive system depth requires higher poles and therefore more expense, it should be avoided. Too little system depth requires increased tension and stronger poles therefore more costs or shorter spans, more poles and increased costs.

Typical encumbrances for a low tension (10 kN) system up to 70 m maximum span are:

single cantilever	-	1,300 mm
double cantilever in overlap span	-	1,550 mm
	-	1,700 mm
double cantilever at a switch location	-	1,550 mm
	-	1,700 mm
double cantilever at switch, sectionalized	-	1,300 mm
	-	2,100 mm

5.9.2 Droppers shall be fabricated from hard drawn copper or stainless steel. They shall be designed to minimize the risk of a broken dropper hanging below the contact wire. The minimum length shall not be less than 150 mm. Dropper lengths are determined on the basis that each length is equivalent to the sag of the messenger (plus contact wire pre-sag) at a span equal to twice the distance of that dropper from the low point of the span, plus a constant representing the shortest dropper in the span.

5.9.3 When the messenger is maintained immediately over the contact wire, the droppers are vertical. Where the messenger does not follow the contact wire and where inclined catenary construction is employed on curves, dropper lengths shall be increased accordingly.

5.9.4 Droppers, except the first and last, shall be spaced uniformally in the span, the number required being a function of span length. The first and last dropper in the span shall be located one half the distance from the support. Six to eight droppers in a 60-70 m span of a simple catenary have been determined to provide good current collection at tension of 6 to 10 kN. Fewer droppers are required in shorter spans. The maximum unsupported length of contact wire shall not exceed 10 m.

Hard spots may be created in the contact wire if droppers are placed too close (within 5 m) to the supports.

5.10 SUPPORTING STRUCTURES

5.10.1 Design Loadings

Structures shall be designed to support the following loads:

a) gravity
b) wind*
c) ice*
d) wire - radial component of tension
- longitudinal component of tension
- stagger component of tension
- dynamic
- uplift
- temperature effects
- erection and maintenance.

* Storm loading conditions of CSA standard C22.3 No. 1-M1979 shall apply.

5.10.2 Structural strength shall withstand the most unfavourable combination of loading and recover upon its removal.

5.10.3 Operational strength requirements, such as deflection, shall be based upon permanent and transient loads that can exist under operating conditions (for example design loads can be imposed by storm conditions under which trains would not operate).

5.11 CANTILEVERS

5.11.1 Cantilevers are generally of tie, strut (bracket) and registration arm construction, employing rod insulators in the tie and strut. Other types use suspension and pin type insulators.

The preferred construction will depend upon the OCS configuration and economics.

5.11.2 Attachments to the pole shall be hinged to permit longitudinal movement resulting from wire expansion/contraction due to thermal causes. The attachment should be of a clamp type (rather than bolt) to accommodate a range of system depths (encumbrances) and to facilitate adjustments.

5.11.3 Cantilever members shall provide a minimum of $\pm$150 mm of radial adjustment.

5.11.4 Two types of cantilever, excluding specials used in tunnels, portal structures and bridges, are generally sufficient.

5.11.5 A single cantilever is used except in overlaps and switches, where a double cantilever is required. Typical types are shown on figures 5.11.5a and 5.11.5b.

5.11.6 Steady arms are generally required but may be omitted in tangent sections when the speed of operation is less than 80 km/hr. They may also be omitted in sidings not connected to the main line, i.e. back track and storage tracks.

5.12 POLES

5.12.1 Poles may be fabricated steel, universal columns (I or H beam), pre-stressed spun concrete or wood. A typical installation is shown in figure 5.12.1.

Figure 5.11.5a
SINGLE-CANTILEVER

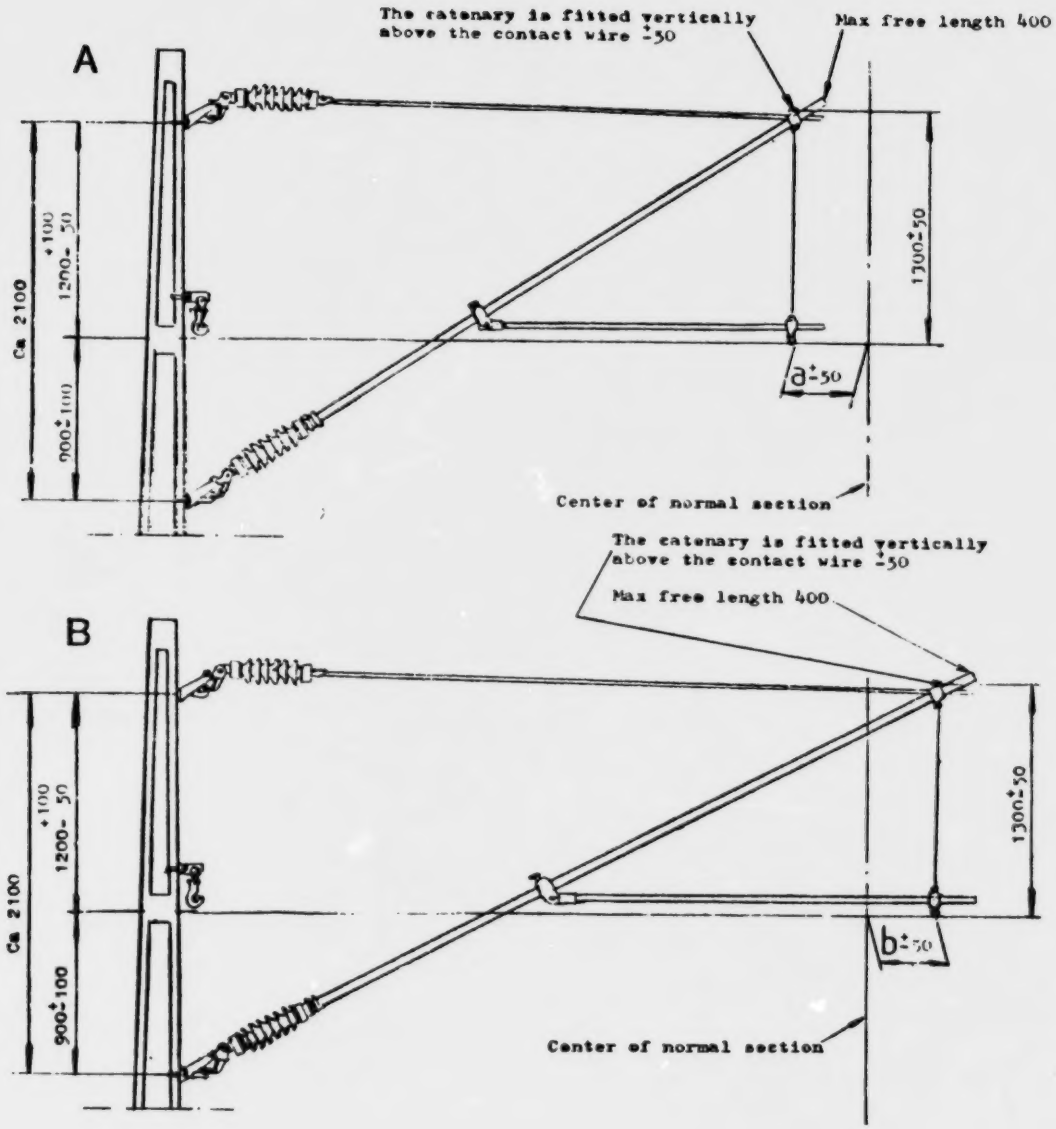


Figure 5.11.5b
TWIN-ARM CANTILEVER FOR SWITCH

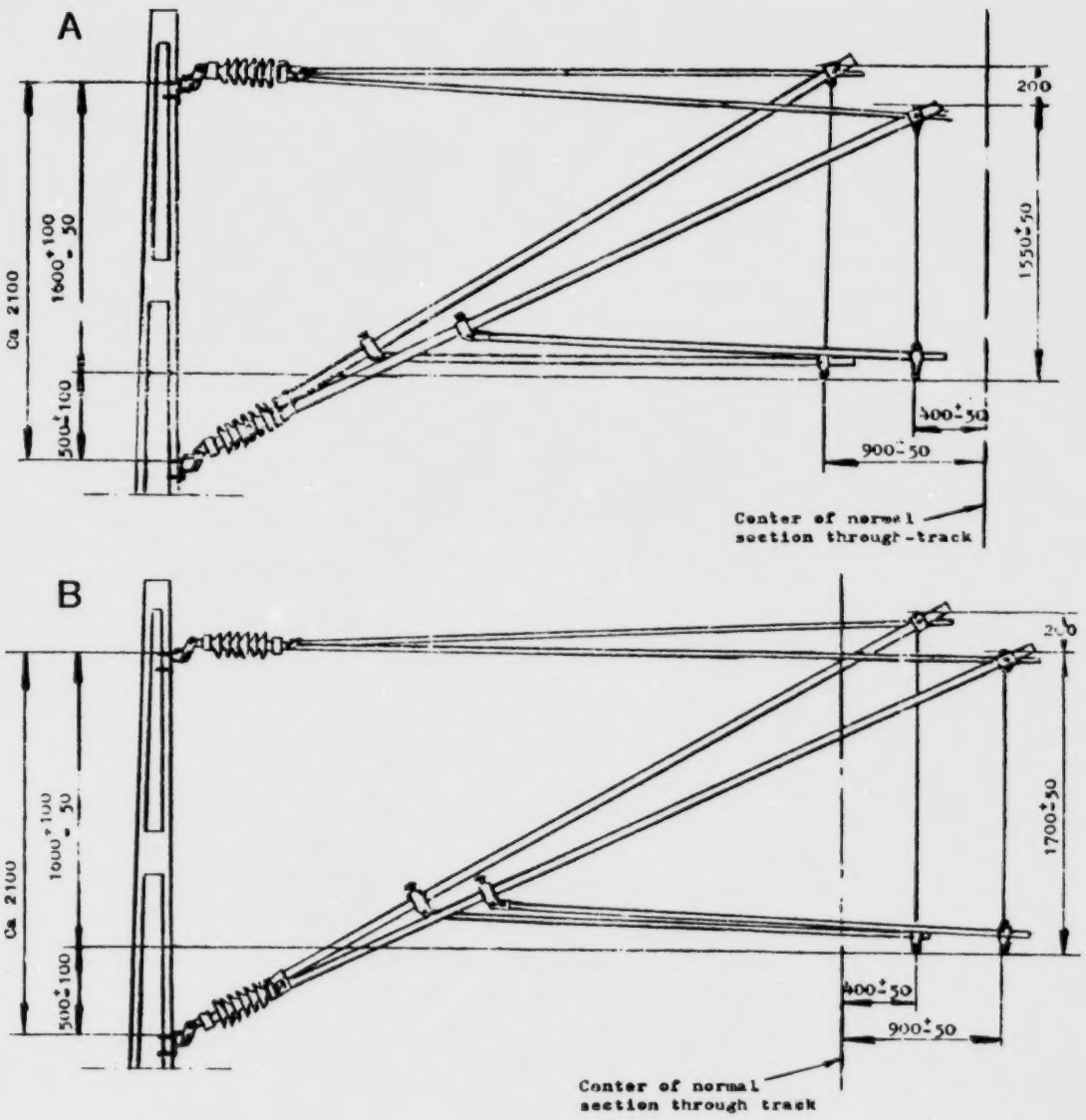
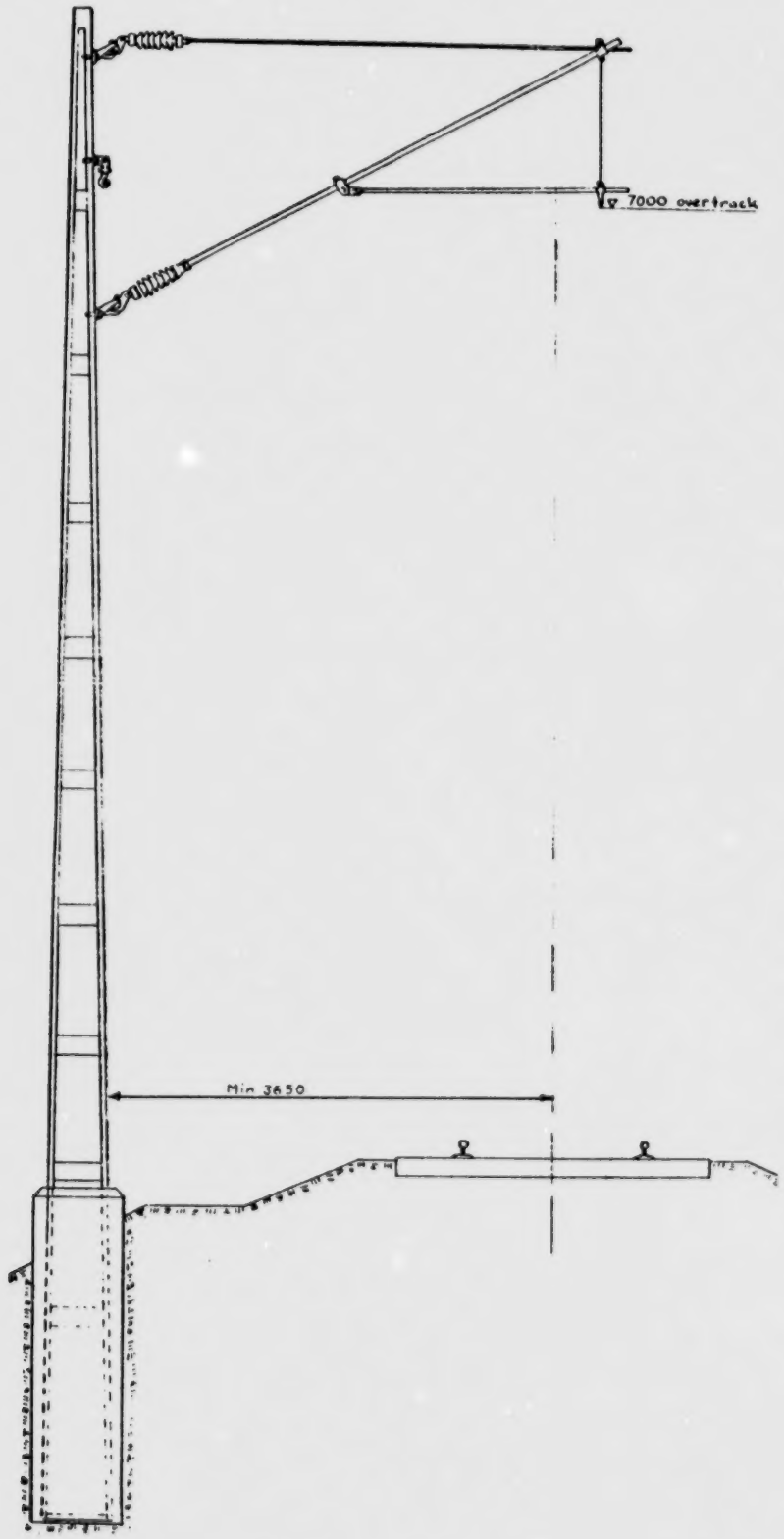


Figure 5.12.1
STEEL-POLE WITH SINGLE (LINE) CANTILEVER



5.12.2 Poles shall be designed to withstand the loadings of 5.10.1 without permanent deformation and to not exceed maximum deflections radial to the track under operating conditions.

5.12.3 The permitted deflection, measured at the contact wire height, is a function of other variables which tend to displace the contact wire from the pantograph.

Generally, it is restricted to value between 50 and 100 mm but larger values can be accepted if other tolerances are reduced to compensate for increased deflection.

5.12.4 Poles shall be designed to resist buckling and torsional effects resulting from cantilever loads.

5.12.5 It has been found desirable from an economic aspect to have poles of different strengths to meet the different requirements i.e. to support single or double cantilevers, weight tensioning, in tangents, in inner and outer curves and in portal structures.

5.12.6 Poles may be designed for direct imbedding in the foundations or earth or with pedestals for bolting to foundations.

5.12.7 Fabricated steel poles shall use structural steel per CSA G40.21-M 300W.

5.12.8 Welding shall conform to CSA W59-1977.

5.12.9 Steel poles shall be hot dip galvanized to a minimum coating of 610 grams per square meter per CSA G164-M 1981.

5.12.10 Poles shall be located within $\pm$50 mm from their specified location radially from the track and within $\pm$1,000 mm from their specified location longitudinally along the track.

5.12.11 They shall be erected vertically within a plumb of 1 in 200.

5.13 FOUNDATIONS

5.13.1 Foundation designs take into consideration soil conditions, i.e. crushed rock, gravel, sand, clay, bedrock, etc.

5.13.2 Resisting moments are calculated from formulae derived for the conventional parabolic and linear soil pressure distribution diagrams which are available from soil mechanics text books.

5.13.3 Depth, type and dimensions of foundations are determined from these formulae.

5.13.4 In isolated areas, the cost of concrete, forming and labour has been found prohibitive. In such cases, pile-driven H beams of adequate dimension and length can be an economical alternative.

5.13.5 Pile-driven installations can also be economical when track access time is minimal.

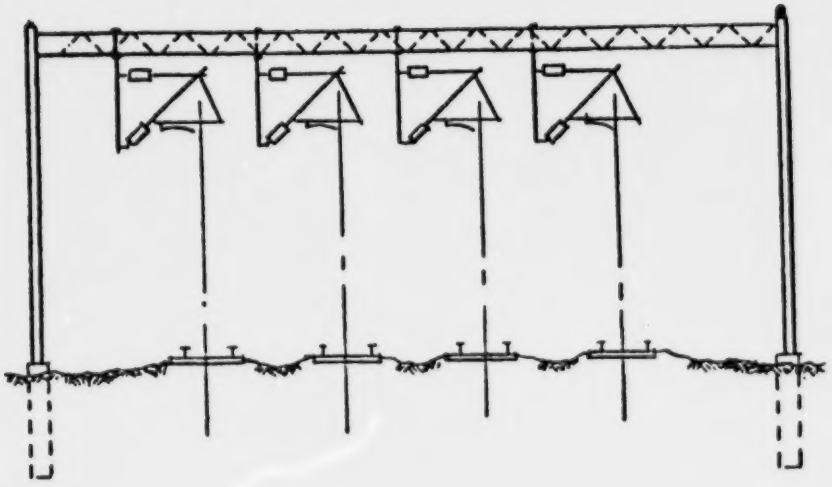
5.13.6 Certain soil conditions are suitable for machine drilling. Poles can then be set with compacted backfill of the drilled material topped with concrete.

5.14 PORTALS/HEADSPANS

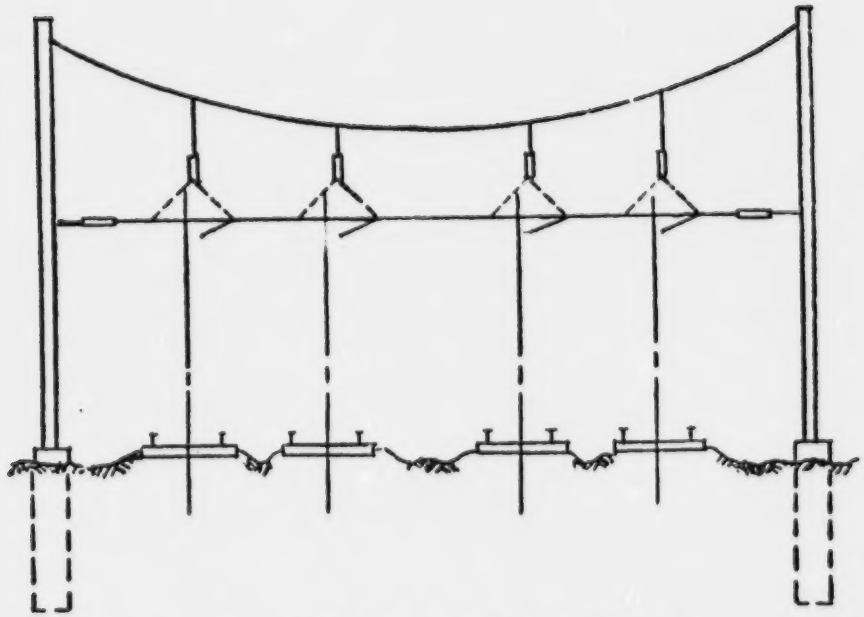
5.14.1 Multiple track installations may be made using either portals or headspans as illustrated in figure 5.14.1.

5.14.2 Portals use a beam, from which cantilevers are attached, to span (bridge) the tracks. The beam is supported by a pole installed at each end. This beam may be of either fabricated (latticed) construction or a solid beam of H or other cross-section.

Figure 5.14.1

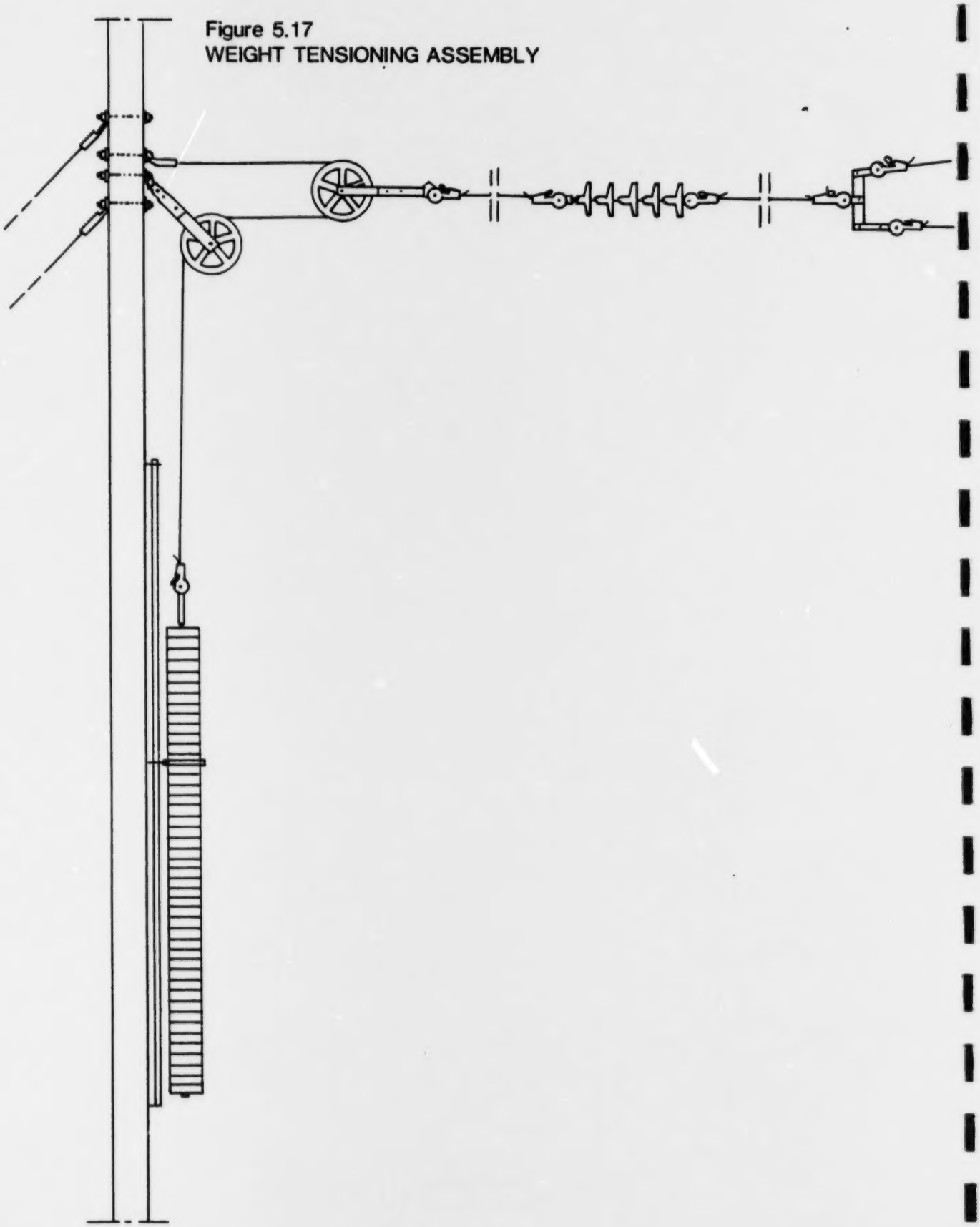


PORTAL STRUCTURE



HEADSPAN STRUCTURE

Figure 5.17
WEIGHT TENSIONING ASSEMBLY



5.14.3 A headspan uses a messenger wire and a span wire, from which cantilevers are suspended, to span the tracks. The supporting poles require side guys. This type of construction, while less rigid than the portal structure, is generally more economical than portal structures.

5.15 GUYING

5.15.1 Head guys shall be provided at mid-point anchors, weight tensioning assemblies and deadends. Guys shall be attached as near as possible to the point of load they are resisting. Space permitting the lead/height ratio shall be 1:1.

5.16 ANCHORS

5.16.1 Anchors may be plate type, deadmen (wood poles) or commercially available patent types for use in soil and patent type anchors for use in rock. They shall be designed to withstand the applied loads without raising. Soil density figures shall be obtained for the particular soil conditions. The anchor shall develop the holding power of the guy strand.

5.17 WEIGHT TENSIONING ASSEMBLY

5.17.1 Weight tensioning assemblies shall be installed at the ends of sections (at the end of half-sections if only a half-section is involved) of constant tensions systems. The weights installed are a function of the wire tensions and pulley ratios of the assembly. A typical assembly is shown by figure 5.17.

5.17.2 The balance weight may be either grey iron castings or concrete.

5.18 FACTORS OF SAFETY

5.18.1 Factors of safety shall be provided as follows:

- structures and supports: 1.6
- wires and by the contact wire at 30% wear: 2
- guying: 2.5

5.19 SECTIONING

5.19.1 The maximum length of section between weight tensioning assemblies is a function of the permitted movement of the contact wire along track due to temperature variations. It is also limited by the amount of resistance to this movement developed in the supports.

By experience, maximum section lengths of the order of 1200 to 1600 meters have been found satisfactory.

5.19.2 The mid-point of the section shall be anchored so that the cantilever is restricted from rotating on the pole.

5.19.3 Cantilevers between the mid-point anchor and the weight tensioning assembly shall be free to rotate with more rotation occuring with increasing distance from the mid-point anchor.

As the cantilever rotates, the contact wire is displaced from the track with the maximum displacement occurring at the pole preceding the weight tensioning assembly.

5.19.4 Overlaps shall be installed between tension sections to ensure smooth transfer at the pantograph from one contact wire to another.

5.19.5 The displacement shall be calculated from the coefficients of expansion of the contact/messenger wires over the maximum temperature deviation from average ambient for the maximum half section length.

This figure shall then be included with the other displacement considerations such as stagger, track tolerances, etc.

5.20 DISPLACEMENT CONSIDERATIONS (AT MID SPAN)

5.20.1 The maximum permitted displacement shall be calculated in consideration of:

- Pole deflection;
- Cantilever rotation due to thermal movement of OCS along track;
- OCS erection tolerances;
- Contact wire height;
- Super elevation;
- Blow-off;
- Stagger effect;
- Locomotive sway;
- Pantograph sway;
- Static offset due to curvature.

5.20.2 Since the probability of all displacement conditions occurring simultaneously is unlikely the assumed displacement shall be 0.7 times the sum of all factors.

5.20.3 Blow-off is the lateral deflection of the contact wire due to wind pressure. It shall be calculated from the parabolic equation:

$$d = \frac{wL^2}{8T}$$

where d = deflection in mm
w = wind pressure in newtons per meter of wire
L = span length in m
T = tension in newtons

Wind pressure shall be calculated from:

$$p = 0.6\ C.v^2 \quad \text{newtons/sq. m.}$$

where v = wind speed in m/s

C = drag coefficient having values as follows:

Wires	1.0
Cylindrical sections	0.8
H sections	1.2
Lattice structures	1.8
Flat surfaces	1.4

5.20.4 Wind Speed

The following wind speed criteria are recommended:

5.20.4.1 Operating wind speed: 75-100 km/hr without ice loading. This value shall be used to compute catenary support and wire deflections for the interface with the pantograph system.

5.20.4.2 Design wind speed: per CSA standard C22.3 No. 1-M1979.

5.20.4.3 Exposed areas: railroads placed on very high embankments or very flat exposed areas can be subjected to abnormal wind conditions. Operating wind speed criteria shall be increased by a factor of 1.25 for exposed areas and high embankments

5.20.4.4 Sheltered areas: across track wind speeds in cuts, deep forests or urban areas are less than normal. Wind speeds in sheltered areas can be reduced to 0.8 times that selected for normal operating conditions.

FIGURE 5.20.5

5.20.5 Stagger effect is the additional bulge of the contact wire as depicted in Figure 5.20.5.

5.20.6 Locomotive sway shall be obtained from the manufacturer.

5.20.7 Pantograph sway shall be obtained from the manufacturer.

5.20.8 Track tolerances and super-elevation shall be obtained for the specific railway involved; if not available, those specified by A.R.E.A. shall be used.

5.21 PHASE BREAKS AND SECTION BREAKS

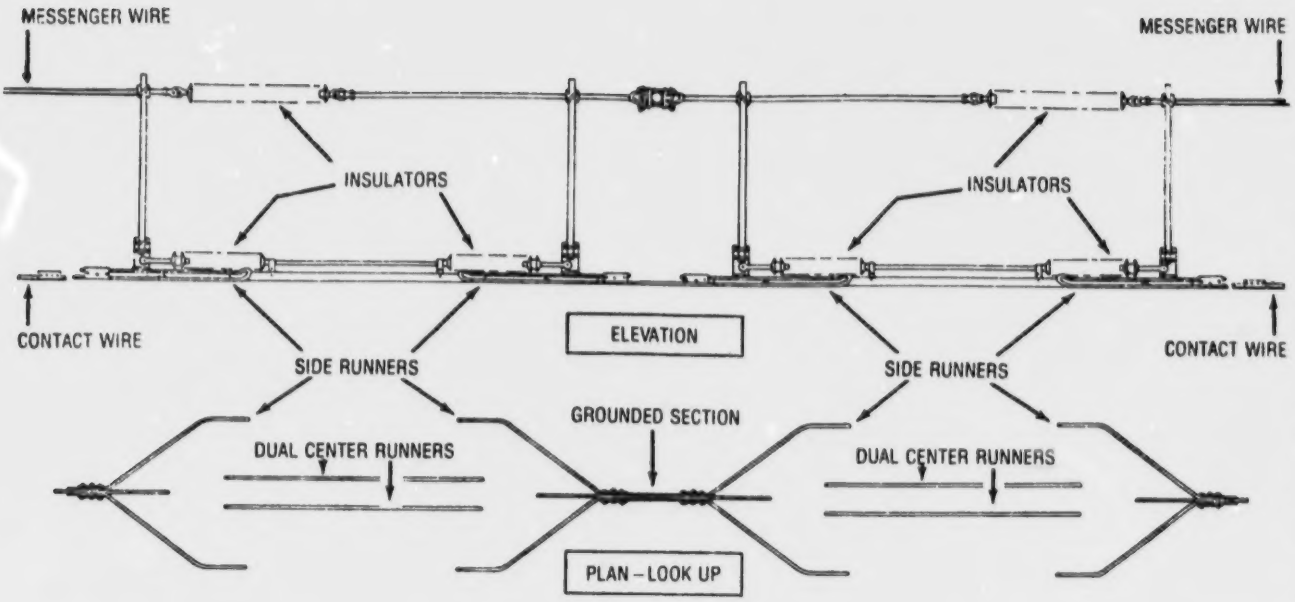
5.21.1 Section insulators shall be installed between sections of the OCS that are fed with different phases of the traction power supply. A typical section insulator is shown in figure 5.21.1.

5.21.2 Overlaps shall be used to provide section breaks where it is desired to sectionalize the line at passing and back tracks for operational or maintenance purposes.

5.22 DISCONNECTS

5.22.1 Disconnects shall be installed to electrically isolate sidings, loops and feed sections as required. Those used to isolate back tracks may be manually operated but those for sidings, and sections should preferably be motor-operated.

Figure 5.21.1
TYPICAL SECTION INSULATOR



5.23 ELECTRIFICATION LAYOUTS

5.23.1 Electrification layouts shall show the following:

- Characteristics of the track i.e., tangent spiral curves, circular curves, passing tracks, back tracks, etc.;
- curve radius, length of curves, direction of curve i.e. left, right;
- point of switch;
- power locations, portals;
- overlap spans, weight tensioning poles, mid-point anchors, anchors and guys;
- span lengths and section length;
- pole number (referred to its km location;
- pole size;
- stagger;
- cantilever type;
- remarks.

6. INTERFERENCE WITH SIGNALLING AND COMMUNICATIONS CIRCUITS

Electric traction lines in proximity to signalling and communications circuits may influence these facilities by electrostatic or magnetic induction or by resistive coupling through the earth.

These effects may be hazardous to personnel and equipment and interfere with the proper operation of such circuits.

6.1 MAGNETIC INDUCTION

6.1.1 Magnetic induction is due to the magnetic field established by the currents in the traction lines and ground which links the communications/signal facilities. The magnitude of the induced voltage is dependent upon the length of the parallel, the separation between the disturbed and disturbing circuits, the magnitude and frequency of traction currents, ground resistivity, traction system configuration and local shielding.

Ground-return circuits are the most common sources of magnetic induction in low-frequency coordination problems. In any location the distribution of current in the earth depends upon the resistivity of the ground, upon the proximity of grounding points and faults, and upon the location of the adjacent grounded conductors.

The coupling factors shall be estimated by assuming the return current to be concentrated in the earth at a considerable distance below the outgoing current.

$$D = 660\sqrt{\frac{\rho}{f}} \text{ metres}$$

where f is the power-system frequency in cycles per second and ρ is the resistivity of the ground in meter-ohms.

Ground resistivity is expressed in terms of the ohmic resistance between opposite faces of a cubic meter of material. The value of the ground resistivity varies through a wide range from 10 to 1000 or more meter-ohms with 100 meter-ohms perhaps most frequently encountered.

The voltage(s) induced into any paralleling facility shall be calculated using the general formula given by Section 3.2 of the guide for the application of the CCITT Directives:

$$e = 2mfM/Ikl0^{-3} \text{ volts}$$

where

f = frequency of the inducing current in Hz

M = co-efficient of mutual induction between the disturbing source of the traction system in mH/km

l = parallel length of exposure in km

I = inducing current in kiloamps

k = shielding factor between 0 and 1

6.1.2 The longitudinal voltage induced in a telephone line shall be limited to 60 volts r.m.s. under normal conditions.

6.1.3 This can be increased to 150 volts r.m.s. subject to the issuance of special instructions to personnel having access to the exposed section of line and the placing of warning signs on accessible parts of installations or apparatus that may be raised to a dangerous potential.

6.1.4 The longitudinal induced emf shall be limited to 430 volts r.m.s. under short circuit conditions.

6.1.5 Generally, magnetic induction into the physical facilities of communications and signals is the primary source of interference to the satisfactory operation of these facilities and of voltages that are hazardous to equipment and personnel. The disturbance to communications occurs primarily in paralleling open wire and cable circuits at voice frequencies. Facilities operating above a few hundred kilohertz, such as carrier systems, are not usually susceptible to transmission impairment.

6.1.6 Voltages induced in all paralleling facilities can be hazardous to both equipment and personnel.

6.1.7 Audio frequency noise induced into a communications or signals physical facility (open wire, cable circuits) located near an electric traction (or power) line is a result of three basic factors:

i) the magnitude of the audio frequency components in the traction line current or voltage;

ii) the coupling between the traction line and the communications facility;

iii) the susceptiveness of the facility.

6.1.8 Harmonic currents in the traction line are mainly generated by thyristor converters of the locomotives although certain harmonics are present in the power feed. The latter are not usually significant in modern power systems.

6.1.9 The magnitude of these harmonics vary with the locomotive and its filtering arrangements. Most pronounced are the third, fifth, seventh and ninth harmonics. (See Clause 8)

6.1.10 Coupling between the communications facility shall be calculated using Carson's equations or using the formulae of the CCITT Directives.

6.1.11 The susceptibility of paralleling metallic facilities is reduced by the shielding effect of other conducting bodies in which currents are also induced which then induces counter voltages into the paralleling facilities. This partially offsets those voltages directly induced into them.

6.1.12 Circuits in cables, whether aerial or buried, are less susceptible to the extent that shielding is provided by the sheath, metallic internal elements or deliberate shields.

6.1.13 Methods of calculating and measuring shielding (screening) are given in the Chapter XII of the CCITT Directives.

The shield factor of cables is more easily obtained by measurement.

Shield factor is defined as the ratio of induced voltage in a circuit with shielding to the voltage that would be induced without shielding.

6.1.14 Railroad tracks, by virtue of return traction current flowing in the opposite direction, have shield factors of the following order:

one or two tracks	-	0.8
three or more tracks	-	0.7

6.1.15 The magnetic coupling between the traction line and the communications/signal circuits shall be calculated for each frequency of concern.

6.1.16 The balance of the communications circuit is obtained by measurement. This figure is a measure of difference that will occur between longitudinal voltages of separate wires resulting in a residual voltage between wires. This is the noise voltage. The expression for this noise is:

Metallic Noise (dBrnc)

$N = 20 \log_{10} e + 92.2 + C + \text{Balance}$

where

e = calculated induced longitudinal voltage to ground at a harmonic frequency.

C = C message weighting for that harmonic frequency expressed in dB

Balance = circuit balance in dB

Circuit balance ratings in dB are:

Poor	-40 (or less negative)
Fair	-40 to -50
Good	-50 to -60
Excellent	-60 (or more negative)

6.1.17 Total noise is calculated from the following expression:

Total noise (dBrnc) =

$$10 \log_{10} (10^{N1/10} + 10^{N2/10} r...)$$

where N_1, N_2 etc. are the metallic noise in dBrnC at each harmonic.

6.1.18 Total noise in excess of 25 dBrnC is not acceptable and shall either be mitigated to less than this level or the circuits replaced with less EMI susceptible facilities.

6.2 ELECTRIC INDUCTION

6.2.1 Electric or electro-static induction is due to the electric field caused by the voltage on the traction lines and within which the communication/signal facilities are encompassed. The magnitude of the electric voltage induced is a function of the configuration of the parallel and the traction voltage. It is independent of the length of parallel and disturbing voltage frequency.

It is dependent on the relative capacitance between disturbed and disturbing facilities and ground.

It can result in charges on metal structures and equipment which is in proximity to the lines that are hazardous (causing shocks which result in accidents) to personnel and also cause interference to communications equipment operating in the VHF radio spectrum.

6.2.2 Electric induction relationships between potentials and charges on each conductor of a system of n parallel conductors using absolute or cgs electrostatic units is given by:

$$V_a = A_{aa}Q_a + A_{ba}Q_b \cdots A_{na}Q_n$$

$$V_b = A_{ab}Q_a + A_{bb}Q_b \cdots A_{nb}Q_n$$

$$V_n = A_{an}Q_a + A_{bn}Q_b \cdots A_{nn}Q_n$$

where V_a, $V_b \ldots V_n$ are the potentials and Q_a, $Q_b \ldots Q_n$ are the charges on the particular conductor designated by the subscript. A_{aa}, $A_{ab} \cdots A_{nn}$ are the potential co-efficients which are determined from the conductor dimensions, their separation from each other and separation from ground.

6.2.3 The hazardous effects of electrostatic induction shall be mitigated by grounding of the metallic structures, when the structure is within a distance D metres determined from the formula:

$$D = 0.024 (f \times E \times S)^{1/2}$$

where

D = distance in metres

f = frequency in hertz

E = traction voltage

S = length of structure parallel to OCS

6.2.4 The radio frequency interferring effect shall be mitigated by its due consideration in the communications system design i.e. appropriate S/N (signal to noise) ratios or use of the UHF spectrum.

6.2.5 The provision of shielding to sensitive signals equipment is a possible requirement.

6.2.6 Electric fields generated by electric locomotives can interfere with the satisfactory operation of trackside radio communications (i.e. Maintenance-of-way, Train Dispatch, and Signal Circuits) especially in the lower (less than 100 MHz) VHF range (30 MHz to 300 MHz). Field strengths as high as 42 dBuV peak/metre have been measured at 15 MHz in proximity to an overhead traction line of 50 kV 60 Hz.

6.2.7 Noise electric field strength under normal conditions, generated in the commercial radio and T.V. spectrums shall not exceed 50 V/m when measured at a distance of 10 m from the track in urban and suburban areas.

6.2.8 Satisfactory VHF operation in this noise environment will depend on transmitted carrier levels and the required carrier to noise ratios. Further, while this level of noise might not break squelch an impulse field can cause clicks to be heard in the receivers.

6.2.9 Since the level of the disturbing field attenuates rapidly with increasing frequency such noise is not expected to adversely affect radio communications in the UHF range (300 MHz to 3 GHz).

6.3 RESISTIVE COUPLING (CONDUCTIVE)

6.3.1 Resistive coupling is that due to the traction current flowing through an impedance which is common to both the communication and traction circuits, usually a common ground resistance.

It is a matter of concern when circuits are in proximity where hazardous voltages can occur on the signalling and communications system as a result of a metallic cross or rise in ground potential.

When the traction circuits cross communications and signal systems there exists the possibility of direct connect should one of them break and fall across the other. Contact between them can also occur under storm loading conditions, if adequate clearances are not provided.

Because traction circuits make intentional use of ground return the traction current can give rise to ground potentials that can be impressed on grounded communications and signal circuits. Large ground potential effects can result under fault conditions where the traction fault current is often of the order of 4000 to 5000 amperes.

6.4 PROTECTION AND MITIGATIVE MEASURES

6.4.1 A thorough and extensive treatment of electromagnetic interference, the derivation of applicable formulae and recommended protective

and mitigating measures are given in the Directives of the International Telegraph and Telephone Consultative Committee (CCITT) published by the International Telecommunications Union (ITU) 1974 Edition.

6.4.2 The subject is also covered extensively in the Engineering reports of the Joint Subcommittee on Development and Research of the Edison Electric Institute and the Bell Telephone System, Volume II 1932, Volume III 1937, Volume IV 1937 and Volume V 1943; by the Electrical Transmission and Distribution Reference Book published by Westinghouse Electric Corporation Fourth Edition; publications of the Institute of Electrical and Electronic Engineers (IEEE); the American Association of Railways (AAR); and numerous textbooks on Coordination of Power and Communications Systems e.g.: Electrical Transmission of Power and Signals by Kimbark, Wiley and Sons.

6.5 HAZARDOUS CURRENT

6.5.1 CCITT considers it hazardous for a person to be in contact with a telecommunications line or installation when that persons body is traversed for a certain length of time by a current having an r.m.s. value exceeding a critical limit which is dependent upon the person's state of health and the path taken by the current through the person's body.

6.5.2 This critical figure shall be assumed to be 15 milliamperes for a person simultaneously in contact with the telecommunications facility and earth or any earthed conductor. (See also Clause 7)

6.6 YARD FACILITIES

6.6.1 Devices in automated yards such as speed radars, presence detectors, wheel detectors, distance to couple circuits (DTC), optical isolators, automatic car identification (ACI), and VHF yard communications are potential victims of EMI (and in some cases a source).

6.6.2 Wheel detectors have been caused to lock out by a 115 MHz CW signal of 116 dBuV/m. Upon removal of the signal it remained inoperative for several minutes.

They are also susceptible to currents in the rail to which the sensor is attached. 1.5 amperes at 20 to 60 Hz will activate this device. At 11 MHz, 1.4 milliamperes will generate the required activating pulse.

6.6.3 Speed radar performance can be significantly degraded in the presence of EMI. Shunt capacitors across the diode detectors shall be provided to mitigate transient effects.

6.6.4 Some presence detectors malfunction in the presence of 60 Hz rail current at 1.5 to 1.6 amperes and also to electric fields above 100 dBuV peak/m at 20 to 30 MHz.

Optical isolator cases and input output leads shall be shielded to minimize susceptibility to undesired signals.

6.6.5 Similar precautions should be taken with distance to couple (DTC) circuits and rectifiers.

6.6.6 Automatic Car Identification (ACI) is susceptible to interference from electric fields exceeding 100 dBuV peak/m at frequencies of 3 MHz to 50 MHz.

6.7 CALCULATIONS

6.7.1 In calculating the effects of electromagnetic induction by an a.c. traction line, account shall be taken of all the exposure sections. Where the sectionalized power segments have voltages between the contact wire and earth that are not in phase, the vector sum of the currents induced into the disturbed facility shall be calculated.

6.7.2 In calculating the effects of electromagnetic induction by an ac traction line under normal operating conditions, the maximum induction effect produced into the disturbed circuit(s) shall be determined.

6.7.3 For those effects arising from a short circuit on the ac traction line the fault will not be assumed to occur simultaneously on several supply sections.

6.8 MITIGATIVE MEASURES

6.8.1 There are several techniques which can be used to mitigate EMI. Since some traction systems cause more disturbance than others the system selected will be based upon the degree of mitigation required and the cost of providing it.

6.8.2 An unbalanced single phase rail/ground return system causes the most interference since there is no counteracting inductive field into the disturbed facilities.

The EMI can be reduced by good rail bonding across joints to improve rail conductivity and thereby increasing proportion of return current in the rails.

6.8.3 An unbalanced system employing a return wire has less EMI. The use of a return wire of approximately the same conductivity as the contact system and mounted at the same height and as close as practicable to it, is most effective.

6.8.4 An effective mitigating technique is to use booster transformers in conjunction with or without a return wire mounted on insulators.

Booster transformers have two windings one of which is put in series with the contact wire and the other in series with the return metallic path (i.e. either the rails or if used, the return wire). The winding

in series with the return path causes an emf to be generated in the return path resulting in a current and electromagnetic field in opposition to the field generated by the disturbing field of the contact wire.

6.8.5 A disadvantage of this technique is the increased impedance of the contact system caused by the booster transformers. This can result in increased costs due to closer substation spacing as well as the additional costs of the transformers.

6.8.6 An auto transformer system acts similar to a booster transformer technique of mitigation because the return traction current sucked out of the rails and returned via a feeder wire is in opposition to the contact wire current.

6.8.7 Severe cases of EMI require replacement of susceptible facilities with insusceptible ones. Physical open wire or cable facilities can be replaced with carrier derived facilities, or radio systems in the UHF and higher frequency ranges. VHF, if not used in proximity to the OCS can also be a satisfactory frequency range.

6.8.8 Circuits can be placed in shielded cables having the required screening.

6.8.9 Where the economics justify it, fibre optics, which is electromagnetic immune, is an ideal solution.

6.8.10 Induction neutralizing transformers and noise chokes are also effective in some instances.

6.8.11 Transpositions in open wire facilities may also be used to balance the induction and therefore reduce metallic noise.

6.8.12 Harmonic filters should be installed on the locomotives to provide as much filtering at source as space will permit.

6.8.13 In the case of signal circuits it may be sufficient to change relays to ones insensitive to traction current frequencies and harmonics. In other cases, most of them, a complete change of the signal system is necessary.

6.9 DEFINITIONS

Electromagnetic Interference (EMI) is the disturbance to conductors and metallic structure caused by the electric and magnetic fields of traction, overhead wires and by the conduction and radiation of harmonic currents/ voltages from electric locomotives. Types of this interference are:

- electrostatic induction
- electromagnetic (magnetic) induction
- conduction (resistive coupling)

Electromagnetic Compatibility (EMC) is the ability of a facility or equipment to function satisfactorily in its electromagnetic environment without introducing intolerable disturbance to that environment or other equipment.

7. GROUNDING AND BONDING

7.1 GENERAL

The grounding and bonding guidelines for railway electrification described in this section cover the operational and safety grounding and bonding of all components of the OCS, associated power feed equipment, all structures and buildings on the railway right-of-way and those objects near the right-of-way which may present a hazardous exposure to the public due to induced or transferred potentials from the OCS.

Grounding is installed for operational reasons or for safety, but any specific grounding connection may serve both purposes.

7.1.1 Operational Grounding

Operational grounding and bonding is installed to ensure that system performance and design criteria are met in respect of voltage regulation along the OCS, the satisfactory operation of ground fault protective devices, steady state and transient overheating of conductors carrying ground return current, and to ensure satisfactory operation of adjacent signalling and communication circuits and other devices which may be affected by ground return currents.

7.1.2 Safety Grounding

Safety grounds are permanently installed or temporarily applied to components of the OCS, power feed equipment, structures, buildings, communications and signalling circuits on, and adjacent to the electrified railway right-of-way, to ensure the safety of railway personnel and the public against hazard of electric shock from either direct contact or induced or transferred potentials.

7.1.3 Classification of Grounding Requirements

As the majority of grounding and bonding arrangements and devices serve for both operational and safety grounding, the following clauses classify grounding requirements according to components to be grounded.

7.1.4 Relevant Standards

The design of grounding and bonding shall be in accordance with this Standard, the latest revision of the Canadian Electrical Code Part I, C22.1 - Safety Standard for Electrical Installations and the latest revision of IEEE Guide for Safety in Substation Grounding IEEE Standard 80.

7.2 GROUNDING OF THE COMPONENTS OF THE OCS

7.2.1 OCS Poles and Support Structures

OCS poles, portal structures, structures carrying head-spans and other structures carrying parts of the catenary system which may be energized, will assume a potential with respect to the "remote ground" due to normal operating currents circulating through the grounding system and fault currents due to ground faults.

7.2.1.1 Each pole or structure shall be grounded in a manner to limit the contact voltage at the structure to 24 V r.m.s. under normal operating conditions and to 230 V r.m.s. under conditions of a ground fault at any point in the interconnectable electrified railway system.

For this purpose, contact voltage shall be defined as the potential difference that exists between any metallic part of the structure and a point on the surface of the ground, one metre from the perimeter of the foundation of the structure.

7.2.1.2 As an alternative to the method given in Clause 7.2.1.1, the method of calculating permissible touch and contact voltages described in the latest revision of IEEE Standard 80 may be used.

When using the IEEE method, the fault duration time shall be equal to the backup protection time on the OCS feeder or the sum of the fault durations in an unsuccessful reclosing sequence (where applicable), whichever is greater.

7.2.1.3 The frequency of grounding of the OCS poles shall be determined as described in Clauses 7.2.1.1 and 7.2.1.2 but the maximum distance between two grounded poles shall not be greater than 500 m.

All portals and other structures in yards, stations and sidings shall be grounded, regardless of the magnitude and duration of the fault current.

7.2.1.4 The physical grounding of an OCS pole or structure shall consist of a grounding conductor connected to the ground return conductor on the structure, run to a junction plate or suitable terminal at the base of the structure. A separate grounding conductor shall be run from this point to the grounded rails or the grounded midpoint of the impedance bond in the signalling rails whichever is applicable. In yards and stations there shall be two separate connections of equal conductor size between the structure and rail. All grounding conductors shall be copper with a one second short time rating equal to the maximum fault current at that location, with a minimum size of 50 mm^2.

7.2.1.5 Where there are two or more parallel tracks at the point of grounding of a structure to the rails, the tracks shall be cross bonded by interconnecting at least one rail in each track with the others in a manner of series connection.

7.2.2 OCS Disconnects and Fuses

7.2.2.1 The metal frame of the disconnect, operating handle and the housing of the operating mechanism shall be grounded by means of a stranded copper conductor of no less than 50 mm^2 to a grounding terminal at the base of the structure on which the disconnect is mounted.

The metal frame of a fuse holder shall have an independent ground connection to the grounding terminal of the structure on which it is installed.

7.2.2.2 The pole or portal structures on which disconnects or fuses are mounted shall be grounded and bonded to the rails in the same manner as described in Clause 7.2.1.

7.2.2.3 In addition to the grounding connections described in Clause 7.2.1 each structure carrying a disconnect or fuse shall be provided with a safety mesh of at least 1 m x 1 m buried under the operating mechanism or handle of the disconnect approximately 30 cm below surface. The mesh shall be connected to the ground terminal on the structure by means of a flexible copper wire of not less than 25 mm^2.

7.2.4 OCS Surge Arresters

If surge arresters are installed outside feeder stations or OCS switching stations, they shall be grounded to a local ground electrode of not less than 10 ohms.

The ground electrode can consist of one or more driven rods or a buried counterpoise. The ground electrode shall be connected to the rails or to the midpoint of an impedance bond in the rails at a point no further than one OCS span away from the location of the surge arrester. The connection should be made with a flexible copper wire of not less than 50 mm^2.

7.2.5 Traction Feeder Stations and Switching Stations

7.2.5.1 Traction feeder stations and switching stations shall be grounded in accordance with the requirements of the latest revision of the Canadian Electrical Code C22.1 and the IEEE Standard 80 Guide for Safety in Substation Grounding.

Notwithstanding provisions of these guides and standards the potential rise of the grounding system of the feeder stations and switching stations shall not exceed 2.5 kV r.m.s. under the worst design fault conditions.

7.2.5.2 The grounding system installed for the traction feeder stations shall satisfy the requirements of C22.1 and IEEE Standard 80 without considering the assistance of rails and grounding of structures in the OCS.

7.2.5.3 The effect of ground wires installed in the OCS, and permanently connected to the station ground of track side switching stations, may be taken into account when designing the grounding of these switching stations.

7.2.5.4 The grounding system of the track side feeder stations and switching stations shall be connected to the rails directly or through impedance bonds at the nearest point practical. The connection shall be made without disconnects or switches, and shall be opened only for the purpose of testing.

7.2.5.5 The ground wire used for connecting the feeder station ground to the rails shall be rated for carrying continuously the maximum return current for worst design contingency and shall have a short time rating based on the maximum design fault current with a duration of one second or maximum backup protection time whichever is longer.

7.2.5.6 As the potential rise of the grounding system of the track side feeder and switching stations may reach 2.5 kV, the following precautions shall be taken with communication circuits and other services:

- All open wire and cable communication circuits entering the substation from remote locations shall have an isolation of 5 kV r.m.s.

- The neutral conductor of any ac service entering the station shall be grounded at both ends.

- Water and drainage pipes entering the station shall have a 3 m insulated pipe section inserted into the pipe outside the station fence line.

7.3 OTHER RAILWAY EQUIPMENT AND INSTALLATIONS WITHIN THE RIGHT-OF-WAY

7.3.1 Rail Switch Mechanisms and Similar Devices

Operating mechanisms and all metallic components shall be connected to the main rails by a flexible copper grounding conductor of at least 70 mm^2.

7.3.2 Station Buildings, Platforms, Yards, Maintenance Shops

All metallic structures, metal roofs, railings, gates etc. shall be grounded to a separate ground electrode of not less than 5 ohm ground resistance. Structures without direct metallic interconnection shall have separate ground terminals which shall be connected to a common ground bus by not less than 70 mm^2 flexible copper conductors.

Step and touch potentials shall be controlled in all these installations in such a manner that the maximum step or touch potential as defined in IEEE Standard 80 shall not exceed 120 V r.m.s. during the worst design fault condition and 12 V r.m.s. under the worst contingency operating conditions.

7.3.4 Level Crossings, Pedestrian Crossings

7.3.4.1 Road crossings shall be provided with galvanized steel ground mats installed under the rails and extending at least 5 m beyond the outer rails, buried approximately 30 cm under the surface. The ground mat shall be bonded to the rails at two points.

7.3.4.2 Protective portals with height gauges shall be bonded to the rails. Each vertical support structure shall have a separate ground connection.

7.3.4.3 Overbridges, gates and all other structures forming part or serving as pedestrian crossing shall be bonded to the rails by grounding conductors of at least 50 mm^2 copper. There shall be a separate ground connection for each independent structure.

7.3.5 Bridges

Steelwork of railway bridges and the reinforcement in concrete bridges shall be grounded and bonded directly to the rails or to the midpoint of impedance bonds in case of signalled rails. The local grounding electrode shall have a ground resistance of not higher than 10 ohms.

There shall be a separate ground connection for each 30 m length of bridge structure with all ground connections joined to a common ground terminal and bonded to the rails at one point only. Grounding conductors shall be at least 70 mm^2 copper.

7.3.6 Tunnels

Grounding of steel structures in tunnels shall follow the same guidelines as for structures outside tunnels. When grounding steel liners or steel meshes in concrete lining, care must be taken to avoid excessive circulating current under operating conditions.

7.4 GROUNDING OF STRUCTURES, BUILDINGS AND FENCES ADJACENT TO ELECTRIFIED RAIL TRACKS

7.4.1 Danger Zones

For the purpose of safety grounding, three zones are defined:

Zone 1	-	Within 10 m from the nearest rail
Zone 2	-	Within 10 to 50 m from the nearest rail
Zone 3	-	Within 50 to 250 m from the rails

7.4.2 Groundings in Zone 1

a) Structures and Buildings

All metallic structures including metal roofs of buildings shall be grounded to a local ground electrode and bonded to the rails running two separate 25 mm^2 stranded copper wires.

Metallic roofs shall be checked for the continuity of good metallic contact between parts of the roof which, if necessary, shall be implemented by running a copper wire around the roof.

Similarly, non-metallic roofs shall have a 25 mm^2 copper or equivalent steel wire installed around the perimeter of the roof which shall be grounded locally and bonded to the rails.

For any ac service power supply into the building other than that derived from the catenary (track side power supply), an isolating transformer shall be installed with a test voltage of 2.5 kV between the secondary (building supply) and the primary winding. The neutral of the secondary side shall be grounded to the local ground. The neutral of the primary side and the primary incoming conductors shall be insulated to at least 2.5 kV for a distance of at least 250 m from the tracks.

Metallic water and drainage pipes connected into the building shall have a plastic or other non-metallic insert of approximately one metre length in the approach away from the tracks.

Telephone lines into such buildings should go through 2.5 kV isolating transformers with the metal screen connected to the local ground and the outgoing circuit insulated to at least 2.5 kV for 250 m laterally from the tracks.

b) Fences

Fences in Zone 1 shall be grounded to a ground rod and bonded to the rails or the midpoint of impedance bonds at intervals not greater than 300 m. The point of bonding shall be marked on the fence post.

Fences crossing from Zone 1 into Zone 2 shall have a non-metallic section inserted at the point of crossing into Zone 2. This can be of wood or any insulating material and shall be at least 2 m long.

c) Pipelines

See Section 7.5

d) Fuel Tanks

See Section 7.5

7.4.3 Grounding in Zone 2

a) Structures and Buildings

Bonding to rails is not required.

Metallic structures and metallic roofs shall be grounded to a local ground electrode. Continuity of metallic roof shall be ensured as under Section 7.4.2 (a).

Incoming low voltage power services and telephone lines shall be protected as described under Section 7.4.2 (a) except that there shall be no bonding to the rails only to the local ground referred to in Clause 7.4.2.

b) Fences

Metallic fences running parallel to the tracks shall be grounded to a ground rod at intervals of 500 m. The point of grounding shall be marked.

For fences crossing into Zone 1, see Section 7.4.2.

Fences crossing into Zone 3 do not need any special measures.

c) Pipelines

See Section 7.5

d) Fuel Tanks

See Section 7.5

7.4.4 Grounding in Zone 3

a) Structures and Buildings

Only local grounding required in accordance with normal building practices and relevant standards.

b) Fences

Fences running parallel to the tracks shall be grounded at intervals of 1000 m.

c) Pipelines

See Section 7.5

7.5 PIPELINES AND FUEL TANKS

7.5.1 Pipelines

Pipelines paralleling or crossing an electrified railway are exposed to induced voltages from the operating and fault currents in the OCS and the transferred ground potential from the rails to the pipe. The exposure is also a function of the method of the installation of the pipe, surface or buried, type of coating, cathodic protection etc.

Each case shall be examined individually taking into account the angle of crossing, the length of exposure, depth of burial and other relevant parameters.

The method of protection shall be agreed with the utility operating the pipeline.

7.5.2 Fuel Tanks

a) Grounding in Zone 1

Fuel tank(s) shall be placed on a ground mat of 2 m x 2 m wire spacing installed under the tank(s) and extending at least one metre beyond the fence of the installation. Each tank shall have separate ground connections to the ground mat. The ground mat shall be bonded to the rails or midpoint of impedance bonds.

The ground mat under the tanks shall be either buried not deeper than one metre or embedded in the concrete slab on which the tank(s) are installed.

In every other respect, the installation shall be treated the same way as buildings in Zone 1.

b) Grounding in Zone 2

The treatment in Zone 2 shall be the same as in Zone 1, except that the ground mat shall not be bonded to the rail. In this case, the ground mat shall have a grounding resistance of not more than 10 ohms, which, if necessary, shall be achieved by supplementary ground rods.

Otherwise, the installation shall be treated the same way as buildings in Zone 2.

c) Zone 3

Grounding of the fuel tanks shall be the same as for Zone 2. Otherwise the installation shall be treated the same way as buildings in Zone 3.

8. UTILITY INTERFACE - UNBALANCE AND HARMONICS

8.1 GENERAL

The nature and characteristics of a typical electric traction load are different from the usual electric industrial load connected to a supply busbar of a public electric utility system. The characteristics which distinguish the typical electric traction load are:

- intermittent load with a quasi-random load cycle;
- purely single phase load or a load with a substantial single phase component;
- harmonics generated by the electric locomotives.

The effect of the traction load on the utility system shall be carefully examined before deciding on the configuration of the power supply to the railway line to be electrified. In addition to the power supply studies usually performed, the following subsidiary studies shall be made:

a) Typical daily load curves based on the maximum demand averaging time agreed with the utility;

b) Frequency and magnitude of in-rush currents due to train starts;

c) Negative sequence voltage on the high voltage supply bus;

d) Harmonic distortion on the high voltage supply bus.

8.2 LOAD CURVES

Daily load curves shall be based on train performance calculations (TPCs) taking cognizance of the normal scheduling of trains and increase in traffic during the planning period.

The daily load curves derived from these studies shall be plotted as an average MW or MVA versus time, where the average MW shall be based on the averaging time for utility billing which is usually 30 minutes or as agreed with the utility.

8.3 IN-RUSH CURRENTS

In-rush currents are caused by starting of trains, trains running through phase breaks and energizing of locomotive transformers.

Locomotive transformers are usually small compared with the size of power transformers in the feeder stations. The inrush current on energization which has a maximum value of about four times rated current with a probability of 10% for a typical locomotive transformer, will normally not result in an appreciable voltage dip on the high voltage utility bus.

While trains use a "soft" starting, the starting time could be within the reaction time of voltage control devices in the systems and will result in a voltage dip on the high voltage supply bus. The same voltage dip occurs when a train is passing through a phase break.

The system shall be designed to satisfy the following performance criteria:

- The voltage dip on the utility's high voltage bus shall not exceed 3% more than three times per day due to starting of trains or trains passing through phase breaks;

- For events occurring more than three times per day, the voltage dip on the utility's high voltage bus shall not exceed one percent for starting of trains or trains passing through phase breaks.

8.4 NEGATIVE SEQUENCE VOLTAGES

Unbalanced load will result in a negative sequence voltage on the high voltage bus. This negative sequence voltage causes an increased current in one phase, and an increased rotor current in rotating machines due to the double frequency inverse rotating field.

8.4.1 To avoid damage to induction motors, synchronous motors and generators, the incremental negative sequence voltage due to unbalance loading on an electrified railway line shall not exceed the following values.

a) Under normal operating conditions of the railway, the negative sequence voltage on the utility's high voltage bus due to the railway operation shall not exceed two (2) percent;

b) Under abnormal operating conditions of the railway, the negative sequence voltage on the utility's high voltage bus shall not exceed 3% due to the operation of the railway.

8.4.2 The negative sequence voltage on the supply (primary) side of the traction feeder station can be, with sufficient accuracy, calculated from the following simple relation:

$$U_2 = 100 S_{syst} / L_s$$

where U_2 = the negative sequence voltage component of the supply bus voltage in percent of the normal operating voltage

S_{syst} = the short circuit level on the supply bus fed from the utility's system in MVA

L_s = the single phase load on the bus in MVA

8.4.3 The simplest way to reduce unbalance is to distribute the load amongst the three phases. For example, in a centre fed system, it may be possible to feed from phases A-B in one direction, and phases B-C in the other direction. With both feeders carrying the same load P, the resultant unbalance is equal to a single phase load of P. The unbalance is reduced to one half of the unbalance created by the same maximum feeder station load supplied from phases A-B only.

In some cases, when dedicated three-phase high voltage transmission lines connect two or more traction feeder stations, it may be possible to distribute the traction load amongst the three phases.

In most railway electrification schemes, the satisfactory balancing of the traction load amongst the three phases is only rarely achievable, taking into account emergency feed conditions.

8.4.4 The following methods are available to reduce the unbalance loading and the negative sequence voltage reflected into the utility system.

a) Three-phase to single-phase rotating converters. - These machines convert single-phase load into balanced three-phase load and completely eliminate the unbalance as seen from the utility system. They can be also used for power factor compensation. Rotating converters have a very high capital and high maintenance cost. For this reason they are not used in new railway electrification schemes.

b) Three-phase to single-phase static converters. - They consist of a three-phase rectifier and a single-phase inverter connected back-to-back. Unlike rotating converters, they cannot generate reactive power, but draw reactive power from the system. They have a high capital cost and low maintenance cost. Their scope of application is limited because of the high capital cost.

c) Synchronous compensators improve negative sequence unbalance due to their contribution to the fault level. They have a high capital cost and high maintenance cost. Their scope of application is limited due to high cost.

d) Scott connected power transformers can be used as phase balancers with the main secondary winding and the teaser winding connected to two separate OCS feeders. With the load current equal in the two windings, the load reflected into the three-phase system is a balanced three-phase load. Scott transformers have a core rating of about 15% higher than equivalent single-phase transformers and require special winding arrangement. Phase balancing is only effective if the load current in the two windings is approximately equal which can rarely be assured.

e) A single-phase load P between phases A-B can be perfectly balanced by connecting a reactor rated Q = P/ 3 across phases B-C and a capacitor rated Q = P/ 3 across phases C-A. The resulting load currents reflected into the three phase network will form a balanced three-phase load. Balancing of the load deteriorates when the single-phase load departs from value P = Q 3. Balancing can be improved by parallel switching of reactors and capacitors to achieve balance at two or more points and reduce unbalance in the intermediate ranges to an acceptable level. The device has been proposed but not yet used in the field of railway electrification. The device is simple and inexpensive.

f) An improvement on the method described in Clause 8.4.4(e) is a static compensator using the same logic but in a continuously controllable mode. Such a compensator has been built and is in operation in a major railway electrification scheme.

8.5 HARMONICS

8.5.1 Harmonic Generation

Modern electric locomotives built for 25 kV or 50 kV traction service, use on-board thyristor converters to feed DC or AC traction motors. Thyristor converters are a source of harmonic generation into the OCS. The amount of harmonics generated depend on the converter load and firing angle at which the converter operates.

Theoretically, the magnitude of harmonics generated is given by:

$$I_n = I_1/n$$

where I_1 = the 60 Hz, fundamental component of the converter load current in p.u.

$n = 2q \pm 1$ (q = integer)

I_n = the harmonic current of order 'n' in p.u.

It has been found by tests that a better approximation for actual maximum harmonic currents is obtained by using the formula

$$I_n = 3\ I_1/n^2$$

Harmonics generated by the electric locomotives are partly absorbed by shunt elements connected to the OCS, such as harmonic filters, shunt capacitors and the OCS capacitance itself. The balance is injected into the power system through the power transformers in the traction feeder stations. This harmonic injection into the utilities' system has to be limited in order to control the voltage distortion in the system.

The presence of a large third harmonic is a characteristic of traction load. This harmonic passes through the single-phase supply transformer in the feeder stations and is not cancelled out in the power system.

8.5.2 Impact of Harmonics on the Power System

Harmonics injected into the power system can interfere with the satisfactory operation of communication circuits, television sets, electrical devices sensitive to wave shape distortion, and in some extreme cases may even contribute to overheating of small induction and synchronous motors.

The two quantities which characterize harmonic distortion as applicable to railway electrification schemes, are the voltage distortion factor (D.F.) on the primary bus of traction feeder stations, and the r.m.s. value of weighted harmonic currents injected into the power system, the I-T Product.

There are other characteristics frequently quoted which are related to the distortion factor and I-T Product such as TIF, telephone interference factor and the line notching.

8.5.3 Definition of D.F. and I-T Product

The Distortion Factor D.F. is defined as:

$$D.F. = \frac{1}{V_f}\sqrt{\sum_{n = 3 \text{ to inf.}} V^2_n}$$

where D.F. = Distortion Factor in p.u.

V_n = harmonic voltages of order n

V_f = fundamental 60 Hz voltage in p.u.

The I-T Product is defined as:

$$I\text{-}T = \sqrt{\sum_{n = 3 \text{ to inf.}} (I_n \ TIF_n)^2}$$

where I_n = harmonic current

TIF_n = Telephone Interference Factor

The values of the TIF are shown in Table 8-1, based on the 1960 TIF Weighting Values.

TABLE 8-1
1960 SINGLE FREQUENCY TIF VALUES

Frequency	TIF	Frequency	TIF	Frequency	TIF
60	0.5	1020	5100	2460	10340
180	20	1080	5400	2580	10600
300	225	1140	5630	2820	10210
360	400	1260	6050	2940	9820
420	650	1380	6370	3000	9670
540	1320	1500	6680	3100	8090
660	2260	1740	7320	3660	6130
720	2760	1860	7820	3900	4400
780	3360	2100	9830	4020	3700
900	4350	2220	9330	4380	2190
1000	5000	2340	9840	5000	940

8.5.4 Limits of the D.F. and the I-T Product

There are no Canadian Standards to limit harmonic distortion in power systems. Utilities have their own guidelines used in customers' contracts and equipment specifications.

Based on current utility practices, guidelines in the United States (IEEE Guide for Harmonic Control, 1979) and the United Kingdom, the following tentative limits are proposed.

8.5.4.1 Distortion Factor

a) On power system busbars dedicated to railway load, the D.F., due to the railway load, shall not exceed 5%, and the harmonic voltage due to any single harmonic shall not exceed 1.5% of the fundamental.

b) On power system busbars from which other than railway load is also supplied, the D.F. due to the railway load, shall not exceed 3% if the bus voltage is 100 kV or higher and 5% if the bus voltage is below 100 kV. The harmonic voltage for any single harmonic shall not exceed 1% and 1.5% for these two cases respectively.

8.5.4.2 I-T Product

The I-T Product, due to the railway load on power system busbars dedicated to railway load, shall not exceed 20,000 and on busbars from which other utility load is also supplied, shall not exceed 5,000.

8.5.5 Harmonic Suppression, Filters

8.5.5.1 Harmonic filters are used in railway electrification schemes to reduce the effect of harmonic generation by locomotives on the power system and to prevent resonance and, oscillations in the overhead contact system. The filters mostly employed are third, fifth, seventh and high pass or RC filters.

From the point of view of reducing the D.F. on the power system busbars and reducing the I-T Product into the power system, the best location of the filters is in the traction feeder stations. The filters may be connected to the 25 kV or 50 kV bus or to a third winding of the HV/25 kV or HV/50 kV transformers.

Filters may be installed at other locations such as in the middle of a catenary section or at the termination of a catenary section to control harmonic overvoltages and to prevent resonance or undamped oscillations.

8.5.5.2 The design of filter installation shall take into consideration the following:

a) Integration of the filter arrangements and rating with requirements for shunt compensation and power factor correction.

b) Possibility of filters causing resonance with the power system. Filters shall be tuned to avoid potential resonance points.

c) The rating of capacitors and reactors in the filters shall take into account the harmonic loading and maximum voltage across capacitors banks, reactors and resistors, caused by harmonics superimposed on the fundamental.